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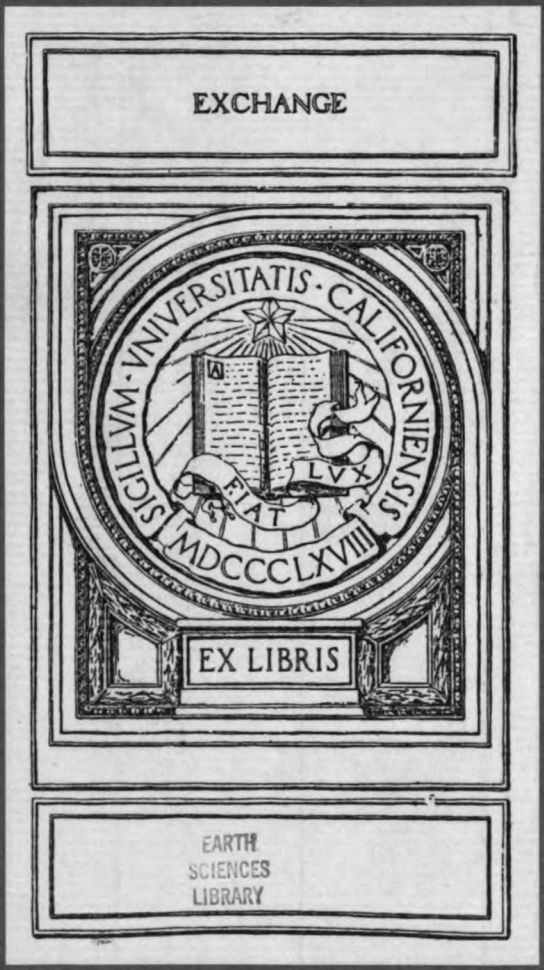


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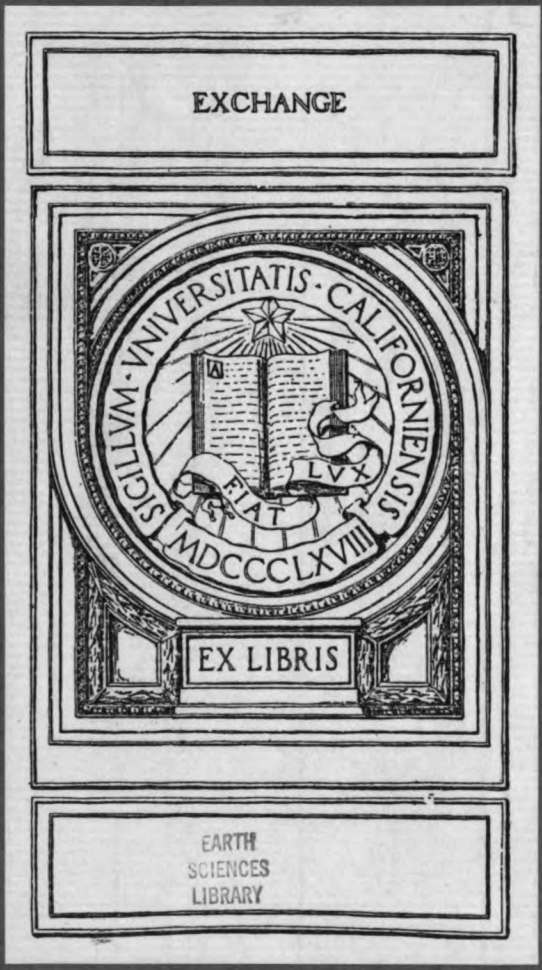


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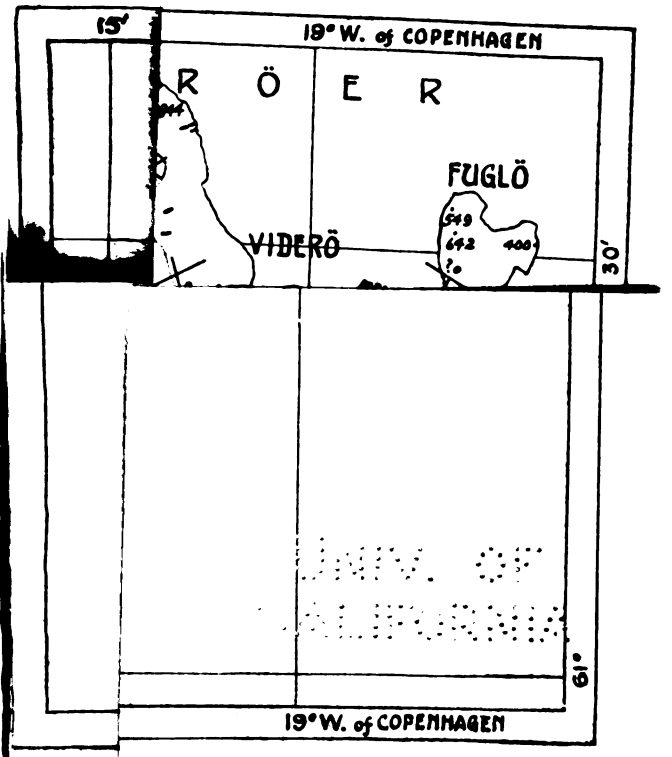


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No. I.—Recent Lines of Fracture in the Færoes in Relation to the Theories of Fiord Formation in Northern Basaltic Plateaux. By Martin A. Peacock, B.Sc., Ph.D., Carnegie Research Fellow, University, Glasgow.

(Read April 8th, 1926; issued June 1st, 1927.)

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## I.—Introduction.

The Færoes constitute an archipelago of twenty islands resulting from the disintegration of a remnant of the Atlantic Basalt Plateau. Previous geological visitors interested in the physiographic evolution of the archipelago have all related the production of the present group of fiord-riven islands solely to erosive agencies. In the course of a brief visit to the Færoes in the summer of 1925 the writer observed that these islands are traversed by a system of clearly visible, recent fracture-lines which are developing into V-shaped clefts and trenches of considerable size and extension. So clearly would a continuation of this process eventually result in a system of fiords and straits, disintegrating and indenting many of the present members of the archipelago, that one cannot resist the inference that the present system of straits and fiords has evolved by a similar process from a similar but older system of fractures.

## II.—Geological Relations and Physiographic Outline.

### 1.—Geological Structure and Relations.

Geologically the Færoes belong to the Kainozoic basaltic region known as the Thulean Province (1926, fig. 1). The islands are composed of a series of gently-dipping basalt-flows with subordinate intercalations of tuff; this volcanic series is intruded by basaltic sills and dykes. In Syderö and Myggenaes an horizon of carbonaceous sediments is intercalated in the basalt series. Acid lavas and intrusives, which are conspicuous in other parts of the Thulean province, are not represented in the Færoes; neither are breccia accumulations present there in any way comparable to the massive products of Pleistocene vulcanism in Iceland. From an interpretation of the inclination of the trap sheets James Geikie estimated the total thickness of the series at thirteen to fourteen thousand feet (1883, p. 237). The foundation of this volcanic pile is not visible.

### 2.—The Source of the Lavas.

There can be no doubt that the basalt sheets were erupted on dry land, Mackenzie's *idée fixe* developed from observations in Iceland (1812, pp. 356-7), and reiterated in his paper on the Færoes (1814 (2), pp. 224-5), that amygdaloidal basalts are

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necessarily submarine lavas, at one time enjoyed considerable popularity. As this theory was based on the assumption that amygdule minerals including calcite, are of pyrogenetic origin, we need not labour to disprove it.

It seems certain that the sources from which the Færoese lavas issued are not within the present area of the archipelago; the position of these sources cannot, however, be inferred with certainty. Considering the variety of tectonic influences which have affected the Færoes it seems unsafe to assume, as James Geikie did (1883, p. 242), that the present prevalent south-easterly dip indicates that the lava sources lay to the W. on the comparatively shallow sea-floor which lies between the Færoes and Iceland. This location may, however, be the correct one.

### 3.—The Age of the Lavas.

The age of the Færoese lavas is also uncertain, as the plant remains from the coal horizon have not yet yielded definite evidence. The general lithological similarity of the Færoe Plateau and the pre-Pliocene basement of Iceland has often rightly been emphasized; and the rocks of both regions are in turn justly comparable with those of the Inner Hebrides. James Geikie finds no reason to differ from the current view of his time that the Færoese lavas are Miocene in age (1883, p. 240), this view having been formulated presumably before Oligocene was interposed between Miocene and Eocene. Pjeturss believes that the basement of Iceland may extend from the Miocene down to the late-Eocene (1910, p. 4). From the plant evidence the Geological Survey of Scotland has adopted the view that the lavas of Mull are Eocene (1924, p. 89); from the evidences of certain fossil beetles, however, it seems necessary to attribute a less antiquity to these rocks.

As the lavas of the Inner Hebrides rest on a visible Mesozoic foundation, and those of the Færoes are separated from their foundation, whether Mesozoic or older, by an unknown thickness of trap, it follows that the Færoese lavas are younger than the oldest lavas of Mull. Then again to assume that the North Atlantic Plateau was built entirely in Miocene times seems to leave too short a period for the completion of the profound geological changes which affected this plateau between the time of the cessation of the volcanic activity and the Pliocene. For these two reasons the writer is disposed to adopt an intermediate view, and regard the age of the Færoese lavas as Oligocene.

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## 4.—The Dip of the Trap Sheets.

Observations of dip have been made by Mackenzie (1814 (2), p. 218), Allan (1814 (1), p. 253), Trevelyan (1823, p. 461), James Geikie (1883, p. 223) and others. Both in direction and in degree there is considerable lack of agreement between these various observations. With some significant exceptions the writer's observations essentially confirm those of James Geikie who already pointed out the extravagance of some of the earlier estimates. As apparent dips have certainly sometimes been recorded as true dips, the writer has adopted a T-shaped sign, the arrow of which, together with the figure indicates the direction and amount of apparent dip, while the leg which meets the arrow midway and at right angles gives the line of observation (Pl. I). As Myggenaes and the N.W. of Vaagö, Stromö and Österö were not reached, James Geikie's indications have been accepted in these localities, and have been entered as plain arrows.

In the Norderöer the trap sheets mostly lie nearly horizontal (Pl. V, fig. 1); towards the S.E. of Bordö and Viderö south-easterly dips of 2° to 3° were observed; in Svinö an apparent west-south-westerly dip of 5° was obtained. In Österö, Stromö, Vaagö, Nolsö and Kolter the lavas dip somewhat persistently to the S.E. usually at less than 3°, but occasionally increasing to 10°. In Myggenaes the dip is easterly at 10°, according to Forchhammer, whose value is accepted by James Geikie. In the southern islands, Sandö, Skuö, Store Dimon, Lille Dimon and Syderö, the general direction of dip is easterly at angles which usually exceed 8°. In Syderö James Geikie states that "the strata incline uniformly to N.N.E. . . . . at 2° or 3° to 15° or thereabout" (1883, p. 223). According to the writer's observations the dip in Syderö is mainly easterly at 8° and upwards; in Pl. III, fig. 1, which was taken from the mouth of Trangisvaag looking N.N.E. at the northern wall of the fiord with a part of St. Dimon in the background, it is clear that the true dip cannot be to N.N.E. In Vaagfjord in the south of Syderö the angle of dip rises to 15° in the northern shore and 20° in the southern wall.

Generalising these observations it appears then that the direction of dip of the trap sheets is mainly south-easterly or easterly, and that the angles of dip increase progressively from zero in the north of the Norderöer to a maximum of 20° in the southern extremity

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of Syderö. The Plateau may thus be regarded as a tabular block which has suffered a progressive, right-handed twist from N. to S. (fig. 1).

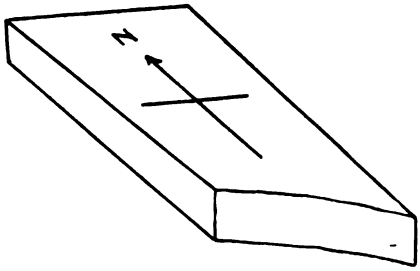


Fig. 1.—The Færoe plateau represented as a tabular block which has suffered a progressive right-handed twist from N. to S.

## 5.—Physiographic Outline.

The physiography of the Færoes is admirably represented on the Danish Ordnance Survey's map of 1916, in two sheets on the scale of 1 : 100,000, with a 25 metre contour interval. With almost extravagant detail the archipelago is mapped on the same department's publication of 1900, in seventy-two sheets on the scale of 1 : 20,000, with contour intervals of 10 metres and 5 metres respectively in the uncultivated and cultivated regions. With the smaller map in his possession the writer had a great advantage over earlier geologists to whom only Capt Born's map of 1806[1] and the Admiralty Charts were available.

The Færoes are essentially tabular relics of a disintegrated and deeply eroded plateau. Slaettaratinde in the N. of Österö, with a height of 882 m. (= 2894 feet), is the highest point in the group; this elevation is approached in the northern parts of the restricted tabular tops of some of the other islands. In Viderö, 884 m. is reached; in Bordö, 755 m.; in Kunö, 820 m.; in Kalsö, 787 m.; in Stromö, 764 m.; and in Vaagö, 722 m.

As these heights are mostly within a fraction of a mile from northern and north-western coastlines it follows that these margins of the plateau present precipitous cliffs to the sea. An extreme case of this occurs in the N. of Kunö where the plateau drops 2690 feet to sea-level on an average incline of 64° to the horizontal.

[1] Reproduced by Mackenzie (1814 (2), Pl. xii), and James Geikie (1883, Pl. xvi).

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Towards the S. and S.E. the heights of the residual tabular summits tail away to about half the above values. Thus the average height of the south-easterly part of the plateau in the Norderöer is about 1600 feet; in Stromö the corresponding elevation is about 1700 feet; in Österö about 1200 feet; and in Sandö about 1300 feet. In Syderö the slope of the plateau surface is from W. to E. from a maximum height of 610 m. (2001 feet) to about 1300 feet.

Thus the plateau surface which slopes in a south-easterly or easterly direction, the slope becoming progressively steeper from N. to S., closely conforms with the bedding of the trap sheets themselves.

## III.—The Fiord System.

The Færoe plateau is dissected by a series of straits and valleys, and indented by numerous fiords. The straits, whose Færoese proper names are usually suffixed by *sund*, and sometimes by *fjord* or *ene*, have a well-defined trend from N.W. to S.E. (Pl. I). In their rectilinear extensions and in the steepness of their walls the straits are often comparable to the typical fiords of Norway. The Færoese straits are invariably narrowest and shallowest at some intermediate point in their length, this point lying approximately at the intersection of the strait with the principal watershed—a line running S.W. to N.E. from the middle of Vaagö to Fuglö. The bottoms of the straits at these points tend to assume, therefore, the form of flat, submerged cols. Kvannesund, Haraldsund, Sundene and Vestmannasund display this feature most clearly.

With a few exceptions the fiords conform to the N.W. to S.E. alignment of the straits. A number of the fiords occur in roughly collinear pairs; the heads of such a pair of fiords are separated by a low col or saddle, while their mouths face away from this col in opposite directions. Where the distance separating the heads of such a pair of fiords is at all considerable the intervening col forms the watershed of a pair of streams which respectively feed the two fiords. All the fiords continue upwards into fiord-valleys whose sectional forms are exactly similar to those of the fiords themselves. The bottoms of these fiord-valleys invariably form the beds of streams draining into the heads of the fiords. Skaalefjord and Fundingfjord are the best examples of a pair of collinear fiords whose upper valley extensions culminate in a

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common saddle. The distance between the heads of these two fiords is 4 miles, while the height of the flat col which separates them is 256 feet. This col is the watershed of the Fjordaa and the Vesterdalsaa which drain into these two fiords respectively. Arnefjord is the only example of a fiord whose upper valley-extension does not culminate in a saddle. This fiord terminates in an acute corrie-like valley whose floor rises steeply from sea-level to the top of the plateau, a height of 2200 feet in a horizontal distance of 1½ miles.

Disregarding fiord-valleys and corries, there are but few valleys in the Færoes. The three largest of these are the Saxen Dal, joining the mid-point of Sundene with the west coast of Stromö; the valley which traverses Vaagö, and contains the two lakes, Sörvaagsö and Fjeldsö; and the one which runs across Sandö from Skuöfjord to Skopenfjord. These three valleys all conform

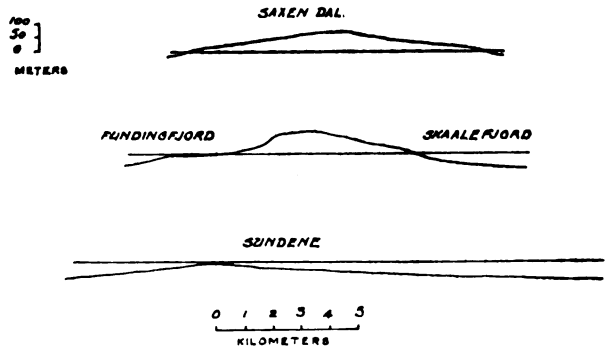


Fig. 2.—Longitudinal sections along typical members of the Fiord System showing that the valleys, the pairs of opposite-facing collinear fiords and the straits are essentially similar negative land-forms.

to the N.W.—S.E. trend of the straits and principal fiords. The floor of the Saxen Dal rises to a flat col, 226 feet high, near the middle of its length; this col forms the watershed of two considerable streams which respectively drain their appropriate portions of the valley. The floor of the valley which traverses Vaagö rises to a height of 370 feet; in addition to the two lakes, it carries the two streams Skjatlaa and Rebsaa. The Sandö valley rises to 417 feet, and it carries three small lakes which are connected to each other and to the sea by streams.

Clearly, then, the straits, fiords, and valleys are but three

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phases, depending on the degree of inundation, of one and the same type of negative landform. Elevation of the land would convert the straits first into pairs of fiords, and then into valleys; depression of the land would bring about the reverse order of changes (fig. 2). By the " Fiord System " will be understood, therefore, this series of mainly rectilinear, steep-sided straits, fiords, and valleys whose principal direction is N.W.–S.E. with subsidiary branches at various angles to this direction.

## IV.—The Goe System.

### 1.—Master Joints.

While cruising along the precipitous coasts of the Færoes the observer cannot fail to notice the innumerable master-joints which often traverse over 2000 feet of bedded traps and tuffs. In their most elementary form these joints are narrow, parallel-sided fissures whose courses are mainly straight, vertical, and at right angles to the face of the cliff which they cut. Less conspicuous than these joints are others the trend of which is parallel to the cliff-faces, and the presence of which is revealed in many of the headlands. There can be no doubt that the high, steep cliffs of the plateau, with their freshly fractured appearance, are related to this second type of master-joint. Notable differential vertical displacement of the plateau blocks separated by joint planes is rarely observable; neither is there visible proof of the widening of a joint into an acute V solely by the relative tilting of these blocks.

The master joints naturally invite the early and vigorous attack of erosive agents. At the base the sea rapidly expands a fissure into an acutely roofed cave which soon widens and recedes sufficiently to allow rowing boats to enter and explore a considerable length of the joint (Pl. II, fig. 2). The Mulegjov, for example, a cave which was manifestly formed by the marine excavation of a master-joint, can be navigated to a considerable depth, and is believed by the local fishermen to continue from its visible entrance near the N.W. extremity of Bordö through to the other side of the island, a distance of one mile. Simultaneous erosion along joint planes mutually at high angles accounts for the formation of the scores of fine stacks which stud the iron-bound seaward margins of the plateau.

Concurrently with marine erosion subaerial denudation attacks

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PLATE II.

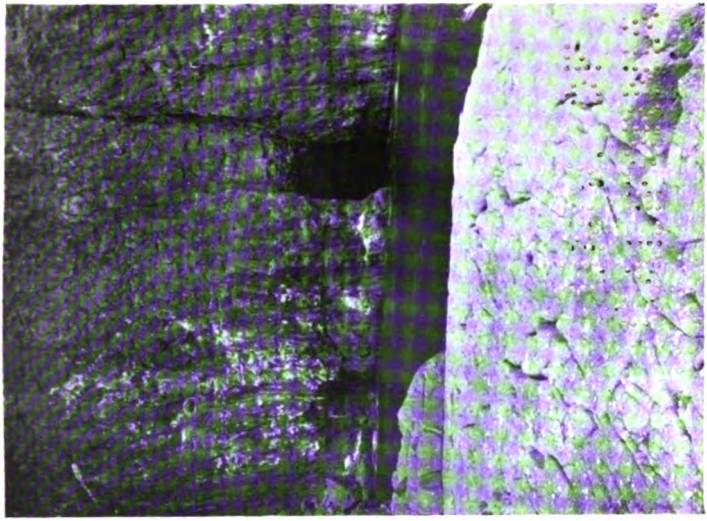

Fig. 2.

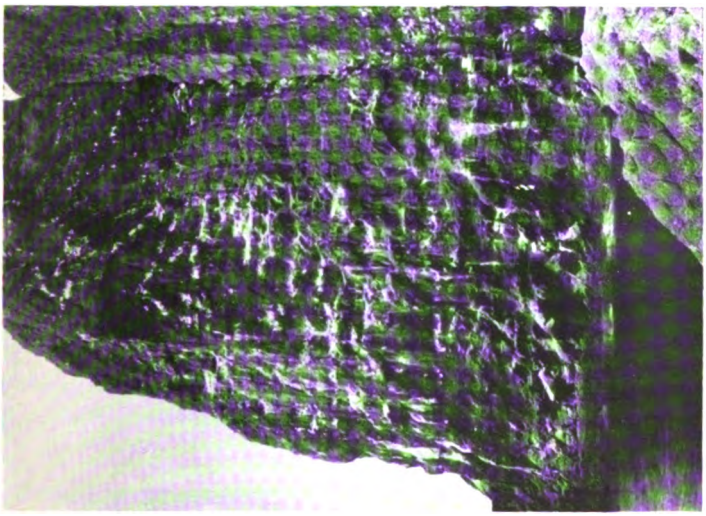

Fig. 1

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the line of weakness where the plane of a joint cuts the surface of the plateau. This line soon attracts the local drainage, and gravitation and intermittent torrents serve to remove at once the rock-material loosened by frost.

The rapid enlargement of master-joints is also effected in the following manner. Sometimes a master-joint is accompanied by one or more minor joints whose planes are roughly parallel to that of the major joint. In this way tall, slender, and unstable slabs of rock are isolated. Rock masses derived from the faces of the minor joints become jammed in their acute clefts; every tremor of these unstable slabs assists gravitation in driving down these natural stone-breaker's wedges; and eventually the tottering

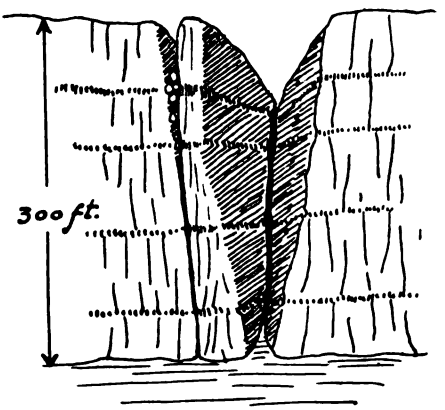


Fig. 3.—Diagrammatic sketch of the Hosteinsgjov, Nolsö, illustrating the method whereby detached material wedged in a subsidiary joint threatens to overthrow a large verticle slab of rock.

masses collapse and disintegrate into the larger V of the major joint, the resulting debris shooting down the steep incline into the sea. The imminence of the culmination of this process is clearly to be seen in the Hosteinsgjov in the S.E. of Nolsö. of which fig 3 is a diagrammatic sketch.

## 2.—Some Typical Goes.

By such processes as these, master-joints develop into considerable clefts which have been popularly recognised as topographic features, and which, when reasonably accessible, have

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been given proper names terminating in *gjôgv* (Fær., pron. *djägv*). Fortunately for the present study the Danish Ordnance Survey has mapped the more prominent of these enlarged master-joints; in the map of 1900 the Færoese spelling is retained, while in the 1916 production the Danish spelling *gjov* (pron. *giow*, "g" as in "go") is substituted. In Iceland long straight gaping fissures in the post-Glacial lavas are designated by proper names ending in *gjá* (also pron. *giow*). In Orkney clefts similar to those in the Færoes are designated by *geo* ("g" as in "go"), and in Caithness by *goe*. In selecting one form of this word for

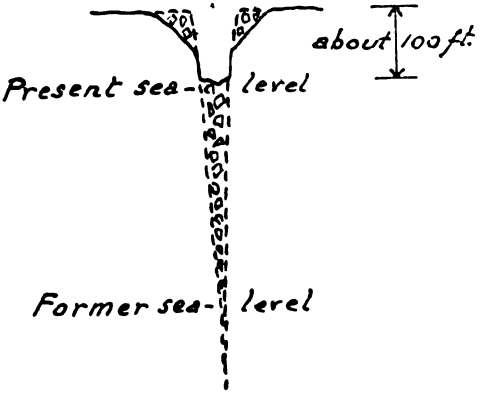


Fig. 4.—Section of the Götegjov, Österö; the full lines indicate the present section of the Goe while the broken lines represent its probable section when the land stood higher than at present.

repeated use it seems desirable to avoid the less attractive Norse variants, and the ambiguous form *geo*, in favour of *goe* which will accordingly be adopted.

Although the goes are most conspicuous where they cut precipitous coastal cliffs, as in the Hosteinsgjov, Nolsö, fig. 3, and Pl. IV, fig. 2, they are by no means confined to such situations. Goes may be seen inland on many steep rock-slopes free from talus. Also they are occasionally noticeable as clean gaps, like gigantic saw-cuts, traversing the sharp medial ridges left by advanced simultaneous corrie-erosion on both sides of elongated islands. Several fine examples of this type may be seen in the high residual central ridges of Kunö and Bordö.

Again, goes sometimes occur in comparatively low-lying and

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gently sloping regions. These goes differ somewhat in appearance from those which cut precipitous rock-faces, and their relation to master-joints is not at once so evident. The low-lying goes take the form of straight trenches whose walls form an angle which is less acute than that of the high-lying goes. These steeply sloping faces are sometimes clothed in turf, and the bed of the trench carries an equable stream. Two observed cases will serve to illustrate this type of goe, and to show how certainly it is also derived from master-joints.

The low eastern end of the Götegjov, where it enters the Götevig on the E. side of Österö, has the section indicated by full lines in fig. 4. The trench is about 100 feet deep, and its flat bottom carries a considerable stream whose bed is as symmetrically

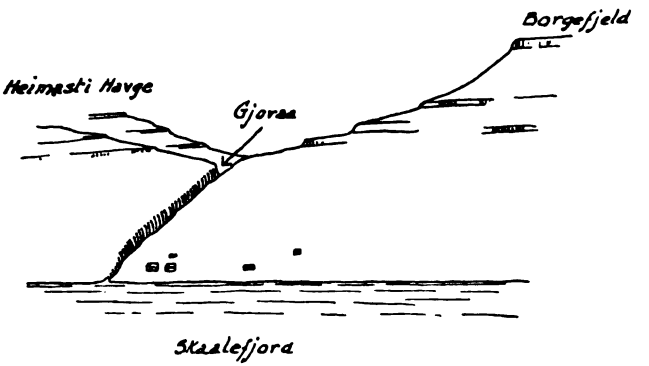


Fig. 5.—View of the Skaalegjov, Österö, looking S.W. from the E. shore of the Skaalefjord.

placed with respect to the walls of the trench. Disregarding all other considerations it is conceivable that this stream could have excavated the trench without assistance. Against this, however, there are the following facts: the trench is popularly recognised and officially mapped as a goe; it extends inland in an almost perfectly straight line for 1½ miles; it is continued W.N.W. across the entire archipelago in a series of seven other straight and collinear goes; other streams carrying similar volumes of water have been unable to cut appreciable trenches in their rock beds; and finally solid rock was not observed in the bed of the goe-stream. Clearly the Götegjov is an enlarged master-joint whose probable mode of development is indicated in fig. 4. At a time

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when the plateau stood at a lower level than at present a master-joint was converted into an acute cleft by the processes already indicated, an intermittent torrent serving to keep the goe thus formed clear of debris. When subsidence took place the removal of debris was checked; the goe became partially filled with rock waste; and the nearly rectangular edges produced by the junction of the walls of the goe with the plateau surface were bevelled to form the present comparatively gentle slopes by the usual processes of degradation. In this way the rather wide rectangular bottom of the Götegjov is explained.

The Skaalegjov, whose eastern end enters the Skaalefjord, Österö, is another example of a goe in low-lying and comparatively gently sloping country. Viewed from the eastern side of the Skaalefjord the goe appears as a straight trench whose section is a rectangular U (fig. 5). By comparison with the houses nearby the goe appears to be about 60 feet wide and equally deep. As in the case of the Götegjov, the Skaalegjov is continued westwards across Österö by two other collinear goes.

### 3.—The Distribution of the Goes.

The Danish Map on the scale of 1 : 100,000 records 210 goes of which 81 have proper names; on the scale of 1 : 20,000 many more goes are shown. Plate I was constructed from the data on the map on the smaller scale; the heavy lines thus indicate the actual extent of conspicuous goes. From a study of this map certain generalisations emerge regarding the nature, location, orientation and distribution of the goes. Some of these general characters have necessarily already appeared in the descriptions of specific examples.

1. In plan the goes appear as almost perfectly straight lines. The longest goe is the Götegjov whose length is 1½ miles; this length is closely approached by many other goes. As goes are enlarged master-joints this rectilinear form is the natural one.

2. Goes are more abundant in precipitous rock-faces, especially coastal cliffs, than in gently sloping country. This does not prove that master-joints are more abundant in steeply-sloping country; it simply reflects the fact that gravitation and aqueous erosion being more potent on steep slopes, master-joints thus located are more readily converted into goes.

3. Goes tend to occur in collinear series which often cross adjacent islands and the strait which separates them. The most

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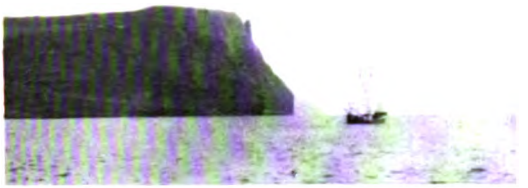

Fig. 1.

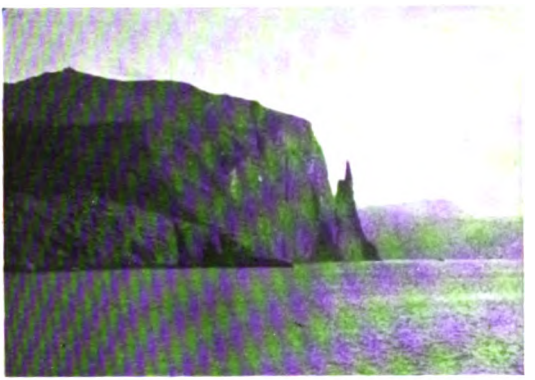

Fig. 2.

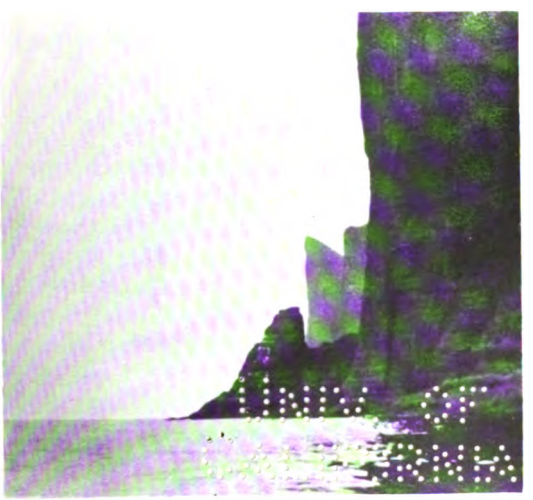

Fig. 3.

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conspicuous example of such series is provided by the eight collinear goes which extend W.N.W. from Götevig, across Österö and Sundene, to the W. coast of Stromö, a distance of 16 miles. This tendency to collinear arrangement would be almost inexplicable were not the goes derived from fractures. The discontinuities in such a series of collinear goes do not, of course, prove discontinuities in the parent master-joint; they simply mark stretches of country whose configuration and drainage were unfavourable to the enlargement of the master-joint whose narrow cleft was therefore concealed in detritus.

4. About two-thirds of the total number of goes lie roughly E.–W.; this orientation is best displayed in the three largest islands, Österö, Stromö and Syderö. As the E.–W. direction is not the direction of easiest fracture it would seem that the E.–W. goes originated from stresses which were so markedly directed that the resulting fractures were not influenced by the configuration of the plateau and its consequent direction of facile rupture. In the Norderöer the goes present a fairly uniform N.E.–S.W. orientation which is perpendicular to the long axis of these elongated islands. These goes appear to have originated from stresses which were only weakly directed, with the result that the consequent fractures followed the direction of easiest rupture, i.e. N.E. to S.W. A few goes lie at various angles to these two main directions. The orientations of these discordant goes probably result either from stresses directed differently from those which produced the E.–W. fractures, or from the conflict between directed stress and predisposition to rupture in a different direction.

## V.—The Influence of Fracture Lines on Drainage.

All the goes, excepting those elementary ones which cut steep rock-faces, and in which enlargement is proceeding chiefly by the help of frost and gravitation, form water-courses. That is to say, master-joints which have developed into goes, with the above exceptions, have all attracted local drainage. The Danish maps reveal numerous cases where a goe-stream, before entering the head of its goe, has a prefectly straight course which is collinear with the goe itself. Here is revealed the early influence of the parent master-joint on the drainage.

In those goes which follow lines of weakness consequent to the

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configuration of the plateau the parent master-joints simply provided potential channels which soon attracted local drainage without modifying its direction. In other cases fracture lines have had a distinct directional influence on the drainage. This effect may be observed clearly in the S.W. wall of the Skaalefjord,

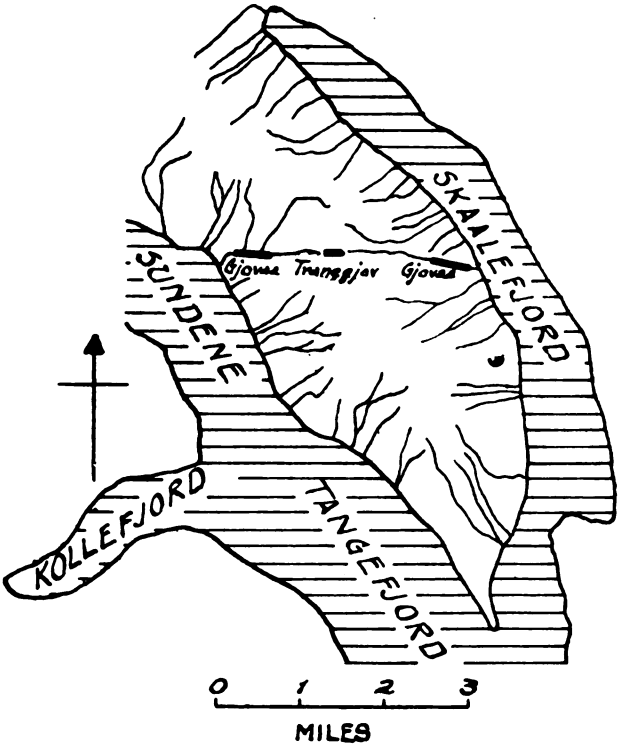


Fig. 6.—Sketch-map of a part of Österö, between Sundene and the Skaalefjord, showing the influence of fracture lines on the direction of drainage.

Österö, which preserves a uniform N.W.–S.E. direction for a distance of 5 miles from its head (fig. 6). This 5-mile stretch of the wall of the fiord is drained by twenty-three streams which, with one exception, run into the fiord in the natural north-easterly direction. The exception is the Gjovaa whose course is E. by S. This stream has adopted the fracture-line represented

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by three collinear goes running approximately E. and W. from Sundene to the Skaalefjord, thus making an angle of about 50° with the natural drainage direction.

Still more significant is the effect of fractures tending to cause the southwards sloping plateau to drain in a westerly or south-westerly direction, almost directly against the dip-slope. Figure

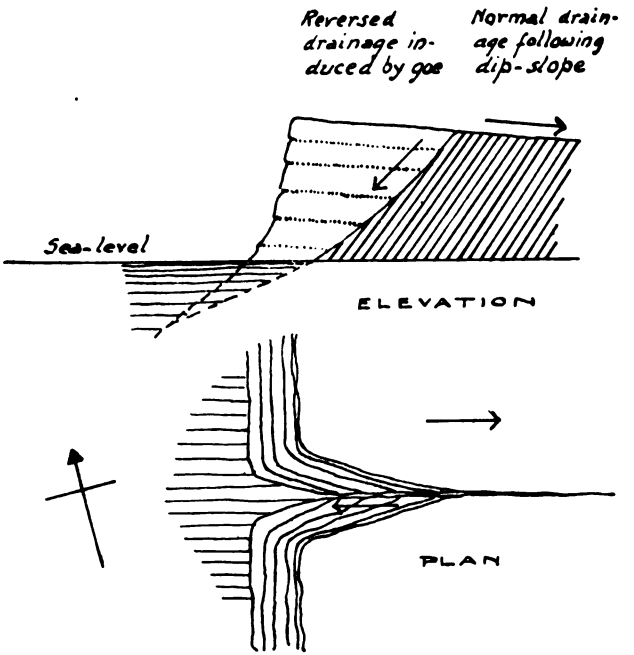


Fig. 7.—Elevation and plan of a portion of the plateau in the N.W. of Stromö, showing how a fracture induces a stream to flow against the south-westerly dip-slope of the plateau.

7, which represents diagramatically a part of the plateau in the N.W. of Stromö, shows how this tendency to reverse the drainage takes place.

## VI.—The Origin of the Goe System.

It has been shown that goes are derived from master-joints; both these features, therefore, have a common origin in crustal stresses which have exceeded the mechanical strength of the trap

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sheets. Fractures may be produced in a hard material such as basalt only by direct tension, or by the tensional components of compound stresses such as flexion, torsion and shear; pure compression could not result in fractures of the nature of master-joints. Any simple or compound stress, with the exception of pure compression, has a tensional component, and will, therefore, if sufficiently great, produce fracture.

When sufficiently stressed, uniform tabular masses of hard material develop cracks which lie normal to the direction of the tensional component or components of the applied stress. Thus rectangular plates of glass subjected to simple tension develop cracks lying normal to the direction of this tensile stress. Similar plates bent about an axis display straight fractures lying parallel to the axis of flection. Plates supported marginally and depressed centrally develop radial and circular cracks with respect to the point of application of the stress; similar cracks would presumably appear in a plate suffering uniform tension in every direction in the plane of the plate. And finally, plates subjected to torsion develop networks of cracks consisting mainly of two sets of straight, parallel fractures intersecting at high angles.

Pre-existing lines of weakness in the stressed tabular masses have a strong directional influence on fracture lines; the more brittle the stressed material, the stronger is the influence. For example it is common knowledge that comparatively shallow scratches on a plate of glass practically predetermine the directions of fractures produced by subsequent destructive stresses in almost any direction; whereas to ensure that fractures will follow even comparatively deep grooves in a softer material, such as a segmented slab of chocolate, carefully directed stress must be applied.

It was seen that the Goe System comprises a network of rectilinear fractures the majority of which lie E.–W., the remainder lying at various angles to this direction; and it was concluded that the E. to W. fractures resulted from well-directed stresses, while the others were caused either by ill-directed stresses influenced by pre-existing lines of weakness, or by stresses acting in a different direction from those which produced the E. to W. goes. As circular or arcuate form is not displayed by the goes or lines of goes, and as any slight indications of radial arrangement result from imperfect approaches to parallelism, and are therefore fortuitous and insignificant, it is concluded, from a consideration

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Fig. 1.

Fig. 2.

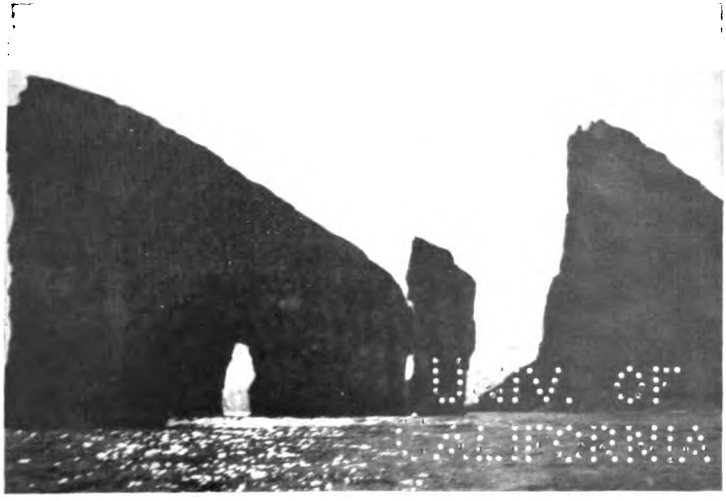


Fig. 3.

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of the above stated results of variously applied stresses on plates of glass, that the Goe System originated from compound crustal stresses which were mainly torsional, and whose principal tensional components acted in a N.–S. line. The fact that the master-joints in their elementary form are invariably sensibly parallel-sided, and that therefore the blocks separated by these joints have suffered no appreciable deflection producing visible gaping, might be regarded as incompatible with the view that the Goe System originated from torsional stresses. This seeming difficulty is removed, however, when it is realised that in such a hard material as basalt the strain, i.e., the elastic deflection, at breaking point will be inappreciably small.

Beyond the fact that the Goe System is certainly younger than the Fiord System, which, it will be seen later, very probably dates from Pliocene times, there is little direct evidence bearing on the age of the goes. From the comparatively slight effects which erosive agencies have had on many of the master-joints, and from the extreme steepness which is still displayed by the walls of all but the oldest and most severely eroded goes, it seems certain that the fractures which originated the Goe System are not older than Glacial, and that they date in all probability from post-Glacial times.

On evidence which the writer was able largely to confirm, James Geikie showed that the latest and present crustal movement in the Færoes is one of subsidence (1883, p. 266). The immediate cause of the regional subsidence of a plateau must be the partial withdrawal of underlying support. It is conceivable that such withdrawal of support could be perfectly uniform, in which case the subsiding plateau would be entirely free from internal stresses. In general, however, withdrawal of support would be non-uniform, and severe internal stresses would be set up in the sinking plateau. Simple flexion about an axis is only a special case of irregular subsidence; the general case of non-uniform withdrawal of underlying support would result in internal torsional stresses, producing, if sufficiently severe, a network of intersecting fractures.[1] Condensing our conclusions into a single statement: it appears that the fractures of the Goe System resulted from severe internal torsional stresses set up in the Færoe plateau by the unequal

[1] Every motorist is familiar with the torsional stresses set up in the chassis and body of his machine by the unequal withdrawal of support due to the deflation of one tyre.



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withdrawal of underlying support during the post-Glacial subsidence.

## VII.—The Origin of the Fiord System.

### 1.—Previous Views.

In 1812 Mackenzie suggested that the long, straight, parallel sounds which separate some of the members of the Færoe group resulted from the removal by erosion of great dykes (1814 (2) p. 226). Before dismissing this speculation, which is based solely on the observation that basalt veins are more rapidly weathered than the trap sheets which they cut, it is worth noting that, as series of long, straight, parallel dykes always follow fracture lines, Mackenzie's conception unconsciously attributes a tectonic origin to the straits.

Glacial erosion, as the main agent, has never been invoked to explain the Fiord System of the Færoes. Indeed James Geikie himself showed that the Færoes were glaciated by local ice which faithfully followed the pre-Glacial topography (1883, p. 247). As Grossmann and Lomas expressed the view that glacial erosion played only a minor part in the evolution of the Færoe topography (1895, p. 14), we need not further consider the possible claims of this agency as the initial cause of the Fiord System.

James Geikie related the formation of the Fiord System to river erosion assisted in a minor degree by glacial erosion. He pointed out, as the writer has also done, that emergence would convert the straits into valleys whose floors would rise to flat cols which would lie on a line coinciding with the present watershed. As the Færoes are at present suffering submergence, James Geikie concluded that the straits were submerged valleys which had been cut by streams running N.W. and S.E. from this common watershed (1883, pp. 255-7).

In his comprehensive treatise on fiords, Professor Gregory briefly notices the Færoes; his treatment of that archipelago is confined, however, to a review of the evidence which shows that the Fiord System is pre-Glacial in age, and that therefore its formation cannot be ascribed to glacial erosion (1913, pp. 164-5). As Professor Gregory's main thesis is that the world's fiord systems have their ultimate origin in networks of fractures produced by the upheaval of the earth's crust in late-Miocene and Pliocene times, and as the Færoes are recognised by him as a fiord region, it

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follows that Professor Gregory relates the origin of the Færoese Fiord System to tectonic agents.

Before discussing the relative adequacy of the erosional and the tectonic theories as applied to the Færoes let us see what would be the result of continued evolution of the Goe System under present day conditions.

### 2.—The Fiord System an Adolescent Goe System.

In fig. 8 is illustrated the drainage of the 16-mile goe-series which commences with the Grotdalsgjov in the western cliff of Stromö and terminates in the Götegjov in the comparatively gently sloping country at the head of the Götevig in the E. of Österö. Each of the goes comprising this series is drained by a stream which obviously follows the continuous fracture-line now intermittently represented by eight goes. The direction of each stream is naturally determined by the configuration of the plateau; the Grotdalsgjov has induced its stream to flow against the south-easterly dip-slope of the plateau in accordance with the mechanism already illustrated in fig. 7. Continued subaerial and stream erosions would clearly convert this goe series into a continuous valley whose extension would be strikingly rectilinear, whose walls would be steep without being as excessively steep as the present walls of the goes, and whose floor would rise to a flat col in Stromö and another in Österö. Slight submergence would convert this valley into pairs of opposite-facing fiords; further submergence would result in a continuous strait.

Without multiplying examples, several more of which might be cited, we may conclude that continued action of the present geological processes would convert the Goe System into a system of valleys, fiords, and straits possessing all the features, excepting orientation, displayed by the members of the present Fiord System. Fiords being immature negative land-forms, there are thus good reasons for believing that the Fiord System is an adolescent goe system.

### 3.—The Tectonic Origin of the Fiord System.

James Geikie's erosional hypothesis to explain the Fiord System of the Færoes appears to be inadequate on several grounds: first, it fails to explain the rectilinear form and network arrangement of the component members of the Fiord System; second, the theory attributes what appears to be excessive erosive power

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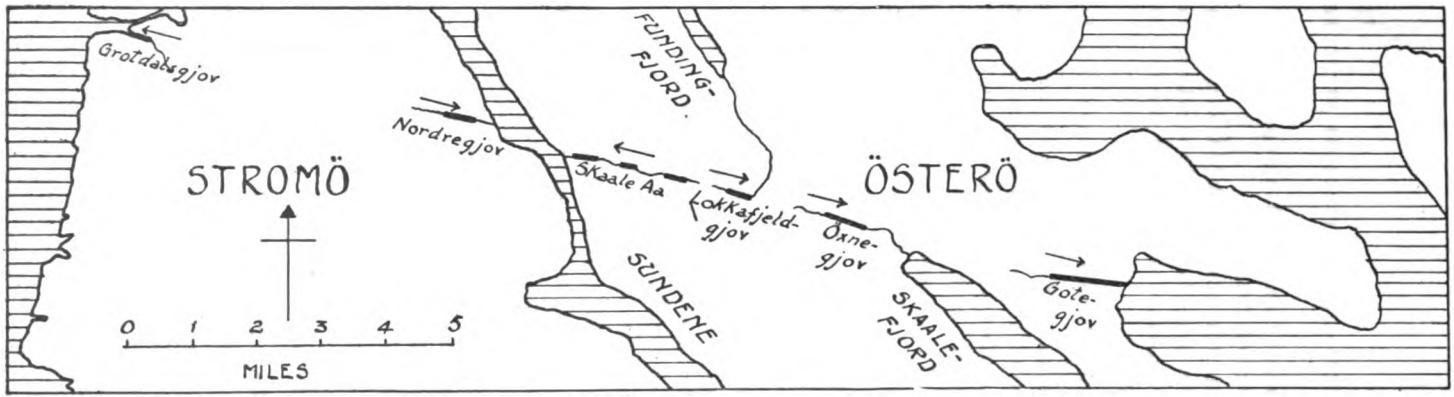


Fig. 8.—Sketch-map of the drainage of the Grotdalsgjov—Götegjov collinear goe-serise.

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to streams which were supposed to have flowed N.W. and S.E. from a line coinciding with the present watershed, and which therefore could not have been notably greater than the present streams; third, the explanation postulates north-westwards flowing streams without suggesting an adequate cause for inducing these streams to flow against the dip-slope of the plateau; and fourth, the theory disregards the existence and consequent influence on erosion of pre-existing lines of fracture.

As continued evolution of the Goe System would apparently result in a fiord system, we are drawn to the conclusion that the Fiord System was derived from an earlier goe system, and that the Fiord System therefore had its ultimate origin in a system of master-joints. By pre-supposing such a system of fractures and then allowing erosion to act in the manner suggested by James Geikie, the difficulties in his purely erosional explanation immediately vanish. The rectilinear form and network arrangement conforms with expectations; no undue call is made on the erosive power of small streams whose chief function is now to remove disintegrated rock-material produced principally by frost and gravitation along lines of facile decay; and the evolution of the present watershed is explained, as already indicated on page 15, by the effect of fractures cutting N.W. coasts inducing streams to flow against the south-easterly dip-slope.

For reasons already given the Fiord System was virtually in its present condition in pre-Glacial times. The fracture system from which it was concluded the Fiord System was derived, must therefore be related to an episode of crustal movement which took place after the volcanic period and before the Ice Age. A brief consideration of the tectonic history of the Færoes shows that such an occurrence is not far to seek.

Towards the close of the volcanic period, probably in the late-Oligocene, the vast Thulean basaltic plateau-land, of which the Færoes now constitute a small remnant, stood completely above sea-level on a platform of Archean or younger rocks. Probably before volcanic activity finally expired Thule commenced to suffer regional subsidence complementary to the Alpine folding. As a result of this subsidence the greater part of Thule foundered below the sea, leaving unsubmerged only a few relics now represented by the eastern basaltic belt of Greenland, Iceland, the Færoes, the Inner Hebrides and a few other areas. At the time

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of maximum submergence these still unsubmerged areas were more restricted than they are to-day.

It is uncertain whether the foundering of the basaltic plateau resulted in the disruption of the present relics with the production of master-joints. From previous reasoning it follows that subsidence would generally entail internal torsional stresses and consequent networks of fractures; as, however, the ensuing tectonic episode, namely the Pliocene uplift, provided more powerful fracturing forces, disruptions produced by the Miocene Subsidence may be regarded as relatively unimportant.

The Pliocene uplift affected Scotland and Iceland, and therefore in all probability the Færoes which lie between these countries. Although there is no marine shelf in the Færoes and no sign of marine cave-formation above the present sea-level, coastal decay is proceeding so rapidly at present that such features might well have been obliterated. In fact it seems probable that at the time of maximum submergence the Færoes were largely or completely submerged and that the ensuing slow uplift left no enduring record on the margins of the plateau.

Thus in the Pliocene uplift we have within the prescribed limits of time a most powerful agent for the production of fracture-lines. From the strong presumption that the Fiord System had its ultimate origin in a system of fracture-lines, and from reasoning similar to that detailed in the enquiry into the probable crustal stresses which originated the Goe System, we are led to the conclusion that the Fiord System of the Færoes was initiated as a network of fractures resulting from severe internal torsional stresses produced in the plateau by the unequal application of upheaving forces during the Pliocene uplift; from the prevalent N.W.–S.E. trend of the principal straits, fiords, and valleys it follows that the principal tensional components of those torsional stresses acted in a N.E.–S.W. line. It will be remembered that the varying dips of the trap-sheets and the configuration of the plateau both indicated that the Færoes are essentially a tabular block which has suffered a progressive right-handed twist from north to south; thus the conception of torsional stresses having produced the fiord fractures received support.

In an earlier section it was stated that neither faulting nor appreciable relative tilting has taken place between the blocks separated by master-joints or goes. It is equally clear from the frequent persistence of the angle of dip from one island to another

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that there is no systematic relative tilting of the plateau blocks separated by the fiord fractures, and that therefore these fractures, like master-joints and goes, were essentially parallel-sided tension clefts.

The Pliocene fracture system doubtless developed into the present Fiord System by processes similar to those now seen at work in the conversion of master-joints into goes. Frost, gravitation, the collapse of unstable slabs of rock between adjacent fractures, marine excavations, and above all the attraction of drainage with the production of streams flowing N.W. and S.E. from a watershed which gradually worked its way from the N.W. margin of the plateau to its present position marked by the summits of the cols of the main straits, pairs of fiords and valleys, all would co-operate to convert the Pliocene tension clefts into goes, lines of goes, and finally into valleys, fiords and straits. In addition, the progress of the Pliocene uplift after the fractures were actually produced would continually expose new sections of the joint-planes to the ravages of the agents of denudation and excavation, and invigorate the streams which had adopted the tension cleft as their courses. The later phases of the uplift would also result in occasional movement in the joints, accelerating their enlargement with the production of more loose material. With the advent of glacial conditions local ice followed the topography which was virtually the same as that of to-day, and by abrasion and the transport of loose material completed the work of Pliocene erosion.

## VIII.—Some Wider Applications of the New Evidence.

The main general result of this study is to confirm in the Færoes the Tectonic Theory of the origin of fiords, a theory which is already firmly established through the work of Professor Gregory. One point in particular has emerged which may make the Tectonic Theory acceptable to some of those who still credit undirected and unaided erosive agencies with the power to excavate networks of elongated, rectilinear rock-basins. A cogent criticism which has been levelled against the Tectonic Theory points out the fact that the fracture-lines to which the fiord systems are thereby related can rarely be demonstrated. Now it has been seen that in those goes which occur in comparatively gently sloping country and which for many good reasons are indisputably related to master-joints,

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these master-joints have already been largely concealed; therefore in fiords, which represent a more advanced stage of similar development, demonstrable lines of fracture are not to be expected, and criticism based on their apparent absence is invalid.

Whereas the Tectonic Theory attaches considerable importance to the gaping of fractures produced by the upheaval of a plateau into a flat dome or arch (1913, fig. 79d), it has been emphasised that this effect is not visible either in the master-joints, goes, or fiords of the Færoes. When considered quantitatively it will be seen that if the span of such a flat arch or dome be great, and lines of disruption occur at the rate of several to one mile, as they do in the Færoes, very considerable arching could take place without producing sensible gaping of each of these many lines of disruption. Thus, without disputing the existence of general arching on a large scale, the writer inclines to the view that the chief efficacy of such arching was in concentrating tensional stresses to the surface, and not in widening the resultant tension clefts. There is good evidence for relating both the Goe System and the Fiord System of the Færoes to torsional stresses which, it has been shown, would generally result from the unequal withdrawal of support, or the unequal application of upheaving forces. It would therefore appear that within the general upheaving movement producing in the main a flat dome or arch, local irregularities occurred in which stresses were mainly torsional, and in which traces of the general arch-structure of the entire upheaved area were obliterated by the more pronounced effects of these local distortions.

The marked effect of visible fracture lines directing and accelerating erosion has greatly impressed the writer, and has been repeatedly emphasised on the preceeding pages. The action of frost and gravitation (Pl. II, fig. 1), the effect of marine excavation (Pl. II, fig. 2), the collapse of unstable slabs of rock between adjacent joints (fig. 3), the directional influence of lines of fracture on drainage (figs. 6, 7, 8), and the great disparity in the dimensions of the channels cut by two streams of equal size respectively occupying beds in a line of fracture and in solid rock, all these features are doubtless observable in other regions of hard rocks which have suffered upheaval and disruption. When these processes have been appreciated the influence of the tectonic agent cannot reasonably be denied, and the conversion of narrow tension-clefts into fiords and other long straight rock-channels

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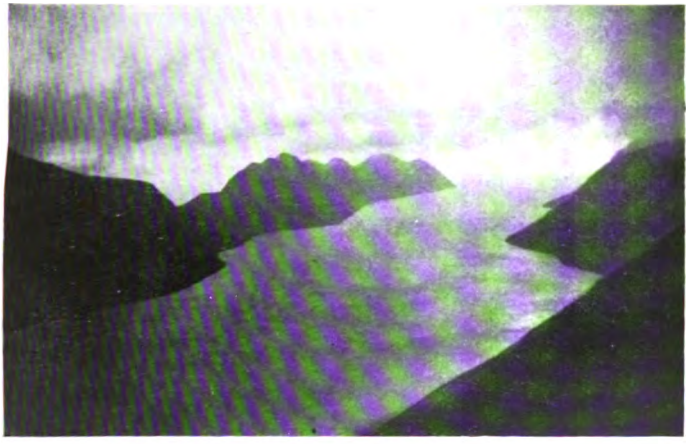

Fig. 2.

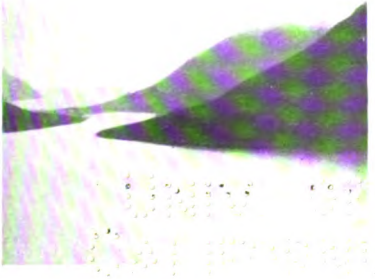

Fig. 3.

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and basins whose walls still preserve a notable measure of steepness becomes a natural process whose early phases may actually be observed.

## IX.—Acknowledgments.

In conclusion the writer would express his thanks to Professor Gregory for the encouraging interest he has shown in this work, and for the many helpful suggestions and criticisms he has offered both in conversation and through the medium of his work, "The Nature and Origin of Fiords."

To Mr. F. Allen, Assistant Map Curator to the Royal Geographical Society the writer is indebted for courteous permission to examine the Society's collection of photographs of the Færoes, and to reproduce selected prints.

For the photograph reproduced in Pl. IV, fig. 1 the writer wishes to thank Dr. Arthur Mayer of Midvaag in the Færoes.

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## XI.—Explanation of Plates.

### *Plate I.*[1]

Sketch-map of the Færoes indicating the distribution of conspicuous enlarged master-joints, the dip of the trap-sheets, the direction of movement of ice, the

[1] *Erratum:* In caption on Map (Plate I), for 'Geo' read 'Goe.'

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position of the principal watershed, and, by means of spot-levels, the general configuration of the plateau.

*Plate II.*

Fig. 1. "Bird rocks," Stromö; photo. by Dr. K. Grossmann. This view illustrates the conversion of a master-joint into a goe chiefly by the aid of frost and gravitation.

Fig. 2. " Bird rocks," near Saxen, Stromö; photo. by Dr. K. Grossmann. Illustrating marine excavation at the base of a master-joint.

*Plate III.*

Fig. 1. Skarvetange, looking N.N.E. from the mouth of Trangisvaag, Syderö, with a part of Lille Dimon in the background; photo. by the author. Here a major joint is in the course of conversion into a goe with the incipient formation of a stack. In this view, in which the trap sheets apparently dip E. at 8°, it is clear that the dip in Syderö cannot be to N.N.E.

Fig. 2. Troldkonefingeren (Witch's Finger), in the S.E. of Vaagö; photo. by Mr. Hepburn. This magnificent stack, which is 1027 feet high, has been formed by erosion along joint-planes of which several may be seen in the photograph.

Fig. 3. " Myling Head," photo. by Dr. K. Grossmann. Typical cliff scenery resulting from joint-planes whose direction is parallel to the margin of the plateau.

*Plate IV.*

Fig. 1. A goe at Bössdala Foss; photo. by Dr. Arthur Mayer. This goe was manifestly derived from a parallel-sided master-joint or tension cleft.

Fig. 2. The Hosteinsgjov, Nolsö, looking N.E. from the head of the goe; photo. by the author. Frost, gravitation, an intermittent torrent and marine excavation have co-operated in converting a major joint into this goe.

Fig. 3. " Drangar and Tindholm," in the W. of Vaagö; photo. by Dr. K. Grossmann. Cliff, stack, and cave formation directed by parallel joint planes.

*Plate V.*

Fig. 1. View from Klaksvig, looking N. along the Haraldsund; photo. by Dr. K. Grossmann. Illustrating the almost level bedding in the Norderöer, and the more mature aspect of the fiord scenery as compared with the cliff scenery.

Fig. 2. View looking W.N.W. from Klakkur in Bordö; photo. by Mr. Hepburn. This view of the Kalsöfjord, with Kalsö on the left and Kunö on the right, illustrates the elongated, rectilinear shape of these islands in the Norderöer.

Fig. 3. View from Kunö, looking S.S.E. over the col which separates Vaagen from Bordö Vig; photo by the author.

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## No. II.—The Sea Lochs of the Outer Hebrides. By J. W. Gregory, D.Sc., F.R.S.

(Read 11th November, 1926; issued 1st June, 1927).

The sea lochs of western Scotland must be studied as a whole. as well as by detailed local studies. A book on "the Origin and Nature of Fiords," (1913, pp. 142-176) stated facts as to their distribution, character, and age, which shew their tectonic origin; but their cause was not considered in detail, as I had not seen all the groups. The last group, the sea-lochs of South Uist and Harris in the Outer Hebrides, I was able to visit during the past summer, thanks to the skilful seamanship and enginecraft of my comrades Mr. W. J. McCallien and Mr. W. R. Flett, under conditions most favourable for their study.

The spelling of the place names is adopted generally from Bartholomew's Half Inch Map of Scotland, sheets 18 and 23, but many are taken from the Admiralty Charts.

### Geological Structure.

The foundation of the Outer Hebrides is a broad band of Lewisian rocks, the oldest of the Scottish pre-Paleozoic divisions. The only later rocks are the red sandstones near Stornoway, that were regarded as Torridonian, until identified by Mr. A. Stevens (*Trans. Geol. Soc. Glasgow*, 1914, xv, p. 59) as Triassic; and some igneous rocks including peridotites of uncertain age and dykes, most of which are Kainozoic, though the quartz-dolerite dykes that trend east to west may possibly be earlier, and columnar basalt in the islets off Loch Maddy which are the westernmost outliers of Skye. The most important structural feature is the mountain line which extends through the Barra Islands and along the eastern side of South Uist, and as Prof. Jehu and Mr. Craig have shown[1] it lies along an eastern overthrust, contemporary with the Caledonian overthrusts of the mainland. Some of the gneiss has

[1] The chief recent contribution to the Geology of the Outer Hebrides is that by T. J. Jehu and R. M. Craig, *Trans. R. Soc. Edinb.* Vol. 53, 1924, pp., 419-441; vol. 53, 1925, pp. 615-641; vol. 54, 1926, pp. 467-489.

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been crushed to breccia and fused to a glassy rock, for which Prof. Jehu and Mr. Craig retain the name of " flinty crush rock." As flint is aqueous silica of organic origin, Dr. Shand's name of pseudo-tachylyte (Q.J.G.S., LXXII, 1916, p. 199; also Hall and Molengraaff, Verh. K. Akad. Wet. Amsterdam, (2) XXIV, 1925, pp. 93-114) seems more appropriate.

Boulder clay is scarce upon the islands, though they contain an abundance of morainic drift; but a new foot-path on the southern side of Loch Skiport, W. of Little Kettle Pool, has exposed small sections of boulder clay, to which my attention was called by Mr. McCallien.

## PHYSIOGRAPHY.

The Outer Hebrides are a chain of three groups—the Barra Islands to the S., South Uist, Benbecula and North Uist in the middle, and Harris-Lewis to the N. The Barra Islands are a drowned mountain band that trended N.N.E. to S.S.W., and their sounds, bays and valleys trend mostly from W.N.W. to E.S.E. The summits, including Heaval, 1260 ft. on Barra, and heights of 891 ft., 678 ft., and 625 ft., on the smaller islands have been blunted and rounded by glacial action. The predominant ice movement, according to Messrs. Jehu and Craig (*op. cit.*, Vol. 53, p. 439) was from S.E. to N.W.

South Uist trends N. and S.; it is 21 miles long by usually between 7 and 9 miles broad. The mountain range on the eastern side rises steeply from the Minch and has a gentler slope westward to the Machers, a low plain strewn with innumerable lakes and tarns. The western coast is long and regular, but the eastern is deeply indented by Lochs Boisdale, Eynort, and Skiport, which break through the mountains and nearly reach the western shore. A tide gate at the head of Loch Skiport prevents the tide from the Minch flooding the western lowlands.

The sea lochs divide the mountains of South Uist into three groups. South of Loch Boisdale is Easaval, 800 ft.; N. of it are the three Boisdale Hills (Beinn Ruigh Choinnich, or Kenneth Hill, 902 ft., Triuirebheinn, 1168 ft., and Stulaval, 1237 ft.); N. of L. Eynort is the group of Beinn Mhor, 1994 ft., Feaveallach, 1723 ft., and Hecla, 1988 ft.

North of South Uist is Benbecula, with two low hills, one 336 ft., on the south-eastern island of the group, and Rueval (409 ft.) near the middle of the main island. North Uist has a broken

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mountain line on the eastern side, including Eaval (1138 ft.), S. of Loch Eport, and the North and South Lees (920 ft. and 823 ft.), S. of Loch Maddy. On the western side of the island are a few hills, of which the highest is Marrival (757 ft.).

Harris and Lewis have a more complex structure. This island begins to the S. with a mountain band extending from S.W. to N.E. along the S.E. peninsula; N. of the West and East Lochs Tarbert the rugged mountains of the Forest of Harris extend across the island with Cleisham, 2622 ft., to the E., and heights of 2439 ft., 2392 ft., and 2227 ft. further W. North of this range are two isolated masses, Mealasbhal, (1885 ft.) to the N.W., and Beinn Mhor (1874 ft.) in the S.E. of Lewis, while the axis of the island extends north-eastward; its highest summit is 918 ft.

The most striking feature of the Outer Hebrides is the contrast between the mountainous eastern side of the Uists and southern end of Harris-Lewis, with the low lake-strewn plains of western Uist, Benbecula, and northern Lewis. A second contrast is that of the narrow inlets from the Minch, with the even coast and broad bays of western Uist and northern Lewis.

The absence of raised beaches from most of the Outer Hebrides is a conspicuous difference from most of the W. Scottish coast; but at Loch Maddy a well-marked beach occurs a few feet above the present sea-level.

## Fiords and Thresholds.

The valleys containing the sea lochs include several which have the essential characteristics of fiords. They have parallel steep sides, as in Loch Seaforth; their long straight banks cut across the country regardless of the geological structure; and some of them are separated from the Minch by the shallow thresholds usually, but not invariably found at the mouths of fiords. The threshold is present at East L. Tarbert where the fiord-like Sound of Scalpay is 12 fms. deep near the entrance and 35 fms. within, N. of Scotasay; at L. Seaforth, which is 20 fms. deep at the entrance and 54 fms. within; at L. Claidh, which is less than 20 fms. at the mouth and more than 30 fms. within; and at L. Sealg (Shell) which is 17 fms. at the mouth, and 26 fms. within.

## Fiards.

A second type of inlet is known as the fiard from its development on the coast of Sweden. Fiards, like fiords, occur in areas of hard

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rock, and are similar in direction and arrangement, but their margins are intensely sinuous, projecting in irregular peninsulas, and having many off-lying islets. The sinuosity of the shore line in fiards has been increased by glacial action having swept away the loose material. Fiards are due to the drowning of fiords, so that instead of the shore being determined by the long straight lower walls it follows the irregular course of the higher contours.

The fiards are developed best in the areas that have been most deeply submerged, such as the Barra Islands, Benbecula, the low ground of northern South Uist, and the low-lying parts of Lewis. Loch Uskavagh, L. Maddy, the southern part of East L. Tarbert, and the entrance to Lochs Erisort and Luirbost in Lewis, are fiards.

### The Regular Trend of the Valleys, and its Independence of the Strike of the Rocks.

The most striking feature of the valley system of the Outer Hebrides is its regularity[1] in direction and independence to the trend of the islands. The Barra group trends S.S.W. and N.N.E., and the predominant direction of the sounds, valleys, and straightest portions of the coast is from W.N.W. to E.S.E. South Uist trends N. and S., and is indented by the E.–W. valleys of Loch Boisdale, Loch Eynort, etc. North Uist shows the E.–W. direction in its southern coast. The island chain turns to the N.N.E. through Benbecula, North Uist, and Lewis. The direction W.N.W. or N.W. holds in Upper L. Boisdale, upper L. Eynort, L. Skiport, L. Maddy, the Sound of Harris, and long straight southern shore of Harris. As the land widens northward, the predominant direction again becomes E. to W., as in L. Sheilg, L. Erisort, the innermost part of L. Seaforth, and further W. on the same line in L. Resort.

The predominant trend and structural lines in the Outer Hebrides run N. and S. in the central part; but they bend in the south to N.N.E. and in the north to N.E. This trend is independent of the grain of the islands, which is shown by the strike and the foliation of the rocks. The strike of the gneiss in the Barra group is shown by Messrs. Jehu and Craig's map (*Trans. R. S. Edin.*, Vol. 53, pl. 4), to be predominantly to W.N.W. or N.W., but in a

[1] F. Heddle, "Gen. Geol. Feat. Outer Hebrides," in J. A. Harvie-Brown and Buckley, "Vert. Fauna Outer Hebrides," 1882, pp. 228, 234, remarks the "striking rectilinearity" of some of the geographical features.

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few places it is N.–S. On the southern part of South Uist the strike is predominantly W.N.W., which is common in the Lewisian gneiss on the mainland of western Scotland. The strike sometimes changes to N.W. and this direction is predominant in the northern part of the island; along the western coast Messrs. Jehu and Craig mark cases of N. and S. strike. In the overthrust eastern area the strike is disturbed; it is often N. and S., but sometimes retains the W.N.W. strike, which probably held in most of Uist before the Caledonian movements. Thus the strike on L. Boisdale is often to the N.W. even on the shore where the loch lies E.–W. On the southern foot of Kenneth Hill the strike is W.N.W.; but along the overthrust fault near the summit of Triuirebheinn it is N. by E. At the entrance to L. Eynort, on the shore of Cearcdal Bay, the gneiss strikes N.E. by E.; but to the W. of that bay the strike is N. and S., and that direction continues westward to Trinival, on the summit of which the strike is 8° W. of N.; further N.W. the form of some hummocks indicates a strike of 18° W. of N.

On L. Skiport, W. of the Kettle Pool, the strikes are confused, being from W.N.W. to N.E. At the schoolhouse near the pier and to the S.E. of Ben Tarbert the strike is E. by N.; on the hill N. of the school the strike is N.N.E., and on the summit of Ben Tarbert it is N.E. On the upper slopes of Ben Tarbert, Mr. Flett observed a series of strikes, most of which range within 10° of N.W. At the flood-gate at the head of L. Skiport the strike is E. by N. A rock hummock on the moorland about a mile further N. has the strike of N. by W.; on "The Long Arm" of L. Shearvag, which itself trends to E. by N. the strike on several outcrops of gneiss is to N.N.W.; a little further west, opposite a rectangular dock-like off-branch, the strike is N. by W. South of the Little Kettle Pool, around the Spotted (or Spotal) Loch at the northern foot of Hecla, and in the moors W. of that loch, the strike of many exposures varies between N.W. and W.N.W.

The rocks at L. Maddy around the pier, golf-course and hotel, have an average strike of N. by E., ranging from N.N.W. to N.E. On the moors between L. Maddy and eastern L. Eport the strikes are chiefly N.W. by ½ N., and N.W. by W. On the southern slope of South Ben Lee, above the narrow entrance to L. Eport, Mr. Flett observed many strikes of which the great majority were due N.N.E.; he found two with the direction W.N.W., which I also observed on one clear exposure, and on the ridge, south of the

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summit; but around the summit of South Ben Lee a series taken by Mr. Flett averaged N.N.E.

A visit to the upper L. Seaforth enabled the strikes to be observed between the head of L. Erisort and East L. Tarbert. The strike on a hill at the head of L. Erisort is N. by W.; but a series nearby taken by Mr. Flett ranged about N.N.W. by W., and in a different direction Mr. McCallien found the strike to be N.N.W. The strike at Upper L. Seaforth is N. by W.; it is almost true N. by the middle reach of that loch; it is N.N.W. at the bend in the road above and S. of Scaladale; it is 10° E. of N. on the shore of W. L. Tarbert near the whaling station; but along the shore farther east it is E.–W. Some exposures along the road E. of the whaling station strike W.N.W.; on the southern shore, near the eastern end of the same Loch, it is N. by W., and up the adjacent hillside it is W.N.W. At the Free Church at East L. Tarbert is a clear strike of N.W.$\frac{1}{2}$ N. South of Loch Tarbert gap the usual strike is N.W. by W., as observed by Mr. Flett.

The predominant strike in this part of Lewis and Harris varies between approximately N. and N.W.; it is often oblique to the lines of the lochs. The chief local change is to about W.N.W. along W. and E. Lochs Tarbert.

The topographic features are sometimes dependent on the strike; for it is coincident with Lochs Tarbert, Eynort and some of the small lochs and branches, such as "The Long Arm" of Loch Shearvag, Upper L. Eynort and its branches, and many of the elongated lakelets on the Machers. The rock that has been weakened by atmospheric decay has been swept out by ice, making shallow basins and tarns. Nevertheless the direction of the majority, especially of the larger and deeper lochs, is independent of the strike of the rocks and is obviously due to some other factor.

## The Rectilinear Clefts and their Relations to the Major Valleys.

One obvious clue to this factor is given by the straight-lined furrows which are striking minor features in the walls of the Scottish fiords. These furrows in the southern slopes of eastern Canna, as seen from the sea, resemble weathered fractures or negative dykes; the Geological Survey Map marks them as faults. Crossing thence to the Outer Hebrides, rectilinear features are distinct on both sides of L. Boisdale. Two conspicuous clefts

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**Fig. 9.—Part of Harris and Lewis. The fresh-water lochs and the sea-lochs which lie in gutter-shaped valleys are in solid black. The fiord valleys and fiord-shaped land valleys, such as Meavaig, are marked by a line of crosses. Scale ½ inch to 1 mile.**

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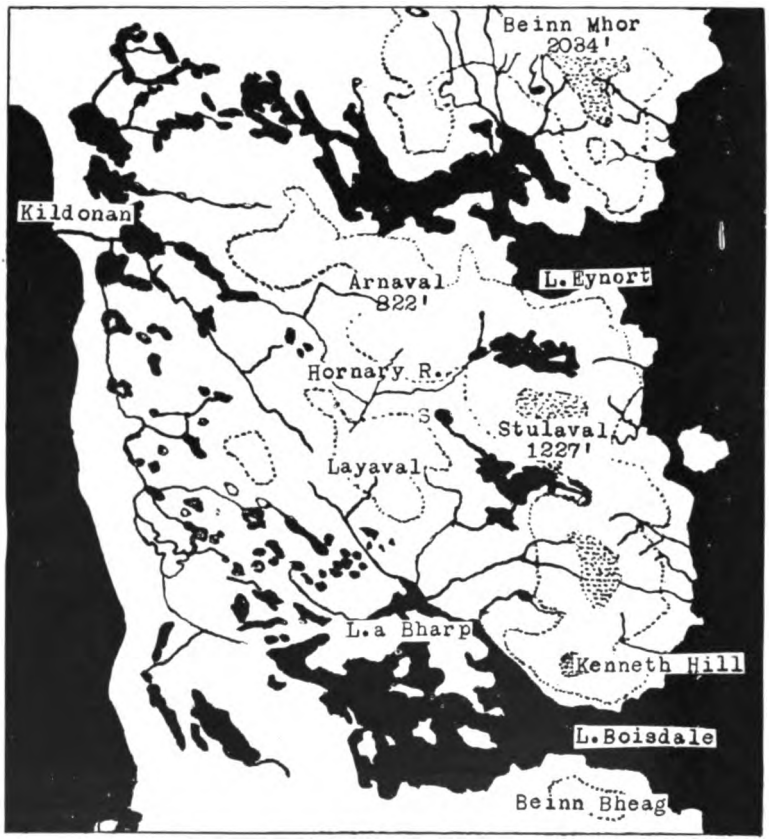


Fig. 10.—Part of South Uist. The lower contour is at the level of 250 ft.; the contour surrounding the dotted areas is at 750 ft. S. is L. Shuravat, the drainage of which has been reversed from the Hornary River to L. Boisdale through L. Stulaval. Scale ½ inch to 1 mile.

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occur on the northern side of the entrance and six parallel furrows down Kenneth Hill. They dip steeply W., and trend N.E. to S.W., as confirmed by observations on shore at Creag Spuir. The clefts cross the foliation of the gneiss at about 110°, as the strike there is generally from W.N.W. to E.S.E. On the S.W. slope of Kenneth Hill in Uisge Scoag is a branched furrow of which the more conspicuous arm trends to N.N.W. and cuts across the gneiss of which the strike varies from W.N.W. to N.W.

On the southern side of L. Boisdale similar furrows cross the ridge of Ben Beg and are parallel to the sides of the local headlands; three other furrows are seen near the entrance above Marulaig Bay. Some of the lochs on the plain W. of the Boisdale Hills appear due to the same features; for while the northern arm of L. Boisdale, which runs W.N.W. to L. a Bharp, has been worn out along the strike of the gneiss, the arm of Loch a Bharp which runs to the W.S.W. lies along one of the fractures.

In the Boisdale Hills the strike of the rocks is often N. and S., and the conspicuous rock faces and long rock exposures, as at the pass N. of Kenneth Hill, trend E. and W. Loch Eynort near its mouth runs W., but after traversing the mountain range of South Uist, it is diverted to the N.W. It also shows a series of conspicuous straight furrows across the strike of the rocks. Thus the southern shore of the loch, W. of Bo Carrach, trends to W.S.W. by ½ W., and then turns abruptly W.N.W. till at the western end of Cearcdal Bay it turns to the N. South of the loch between Bo Carrach and Cearcdal Bay the country is traversed by sharp straight furrows, of which the three to the E. trend to N.W. by W.; the westerly furrow continues the coast line inland to W.S.W. by S. The gneiss on the shore at the western corner of Cearcdal Bay strikes S.W. by W.; but a little farther W. it changes abruptly to approximately N. and S.; in the hills to the W. as far as Trinival (the 634 ft. hill 1½ miles W. of Cearcdal Bay) the strike varies within a few degrees W. of N. The strike on the summit of Trinival is 8° W. of N. Three well-marked clefts trending to S.E. may be seen on the northern front of Arnaval. The view from Trinival shows that upper Loch Eynort and the lochs on the same line (18° W. of N.) up to Loch Fada coincide with the strike of the gneiss. This line is cut across obliquely by a series of approximately E.–W. lochs or branches; this series includes the arm of L. Fada which is continued by the northern arm of Loch Altabrug, the main parts of L. Ollay and L. ceanna Bhaigh, and upper L. Eynort



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above the Narrows, which is in line westward over a low divide with Kildonan Glen.

These E.–W. valleys are old features and were probably cut by rivers draining the western slopes, before the eastern range had been cut through. In contrast to these old valleys are a series of sharp rectilinear furrows which trend about N. to S. or 5° W. of N. One of the most conspicuous crosses the S.W. slopes of Beinn Mhor along the course of the Allt Volaghir; it is continued by the Narrows of L. Eynort and the furrow valley which crosses the head of Cearcdal Glen.

The topography of the L. Eynort basin is therefore determined by a series of E.–W. ancient river valleys, by subsequent valleys trending approximately N.N.W.–S.S.E. along the strike of the gneiss, and by a series of fractures that cut obliquely across the strike of the rocks and older valleys, and form the sharp rectilinear features, clefts and coast lines.

Rectilinear clefts are seen at intervals along the eastern coast N. of L. Eynort, as at L. Hellisdale and Glen Usinish, S. of the Usinish Promontory; but they are less distinct in the lower land further N., as in Benbecula. They again become conspicuous as the land rises in Harris, as on Chaipaval, on the northern side of the Sound of Harris, as deep rock clefts on the shore at Rudha Cluer, and a cleft at Stockinish Island which is in line with a furrow at the head of L. Stockinish.

L. Skiport, in the N. of South Uist, is determined by two trends, W.N.W. and E.N.E. A trend of E.–W., is also conspicuous in the main relief, S. of the entrance, as shown by the hill shading on the Admiralty Chart (No. 2750) and by the course of the valleys and arms of the sea on the northern shore. This E.–W. depression is continued inland from Lowlanders Bay over a low divide S. of Ben Tarbert (546 ft.) to L. Druidibeg on the western plain; the features of this depression indicate that it is an old valley of denudation. The trend W.N.W.–E.S.E. has been developed by erosion along the strike of the gneiss, as in the upper or " Linnhe Arm " of L. Skiport and parts of the southern shore of the outer part of the same loch. The trend to E.N.E. is seen at the main entrance to L. Skiport, at the Stick Loch which discharges to Lowlanders Bay. To the N.W. of Upper Loch Skiport the strike bends to N.N.W., and some lochs adopt that direction, while others trend to E. by N. and E.N.E.

The rocks near the Stick Loch and on the parallel N.W. coast of the Island Loch, strike W.N.W.

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The instability of the drainage in the moorland near Mount Hecla is shown by the Spotted Loch, which receives the drainage from the N.W. corrie. This loch formerly discharged westward to L. Druidibeg through the Long Loch; the outlet was diverted to the N.W. through Whit Stone Loch and L. Fada to Lowlanders Bay. Its present drainage is to Little Kettle Pool through a small trench in the peat, which I was told by the son of the proprietor was cut when that pool was an active fishery centre.

The rectilinear furrows and clefts which are so conspicuous in the Outer Hebrides are tension clefts which represent the smallest of the fiord making fractures. The transition from tension cleft to fiord may be seen on the western coast of Scotland from such parallel clefts as those on the coast of Cowal in L. Fyne, up to the slocs of the Outer Hebrides, the goes of Caithness, and the goes of the Færoes which have been well described by Dr. Peacock (*Trans. Geol. Soc. Glasgow*, xviii, pt. 1). That clefts and fiords are both due to the same cause is indicated by their agreement in age, distribution and parallelism. Such clefts are present on all fiord coasts, and are especially numerous where the fiords are best developed.

## The Valley Networks.

Two features that are especially significant as to the origin of the fiords of the Outer Hebrides are the occurrence of the lochs and arms of the sea in networks, and the passage of the loch valleys through the mountain ranges. Networks of channels are conspicuous on the map of Benbecula and the northern end of South Uist; but they proved on a visit to be fiards in a partially submerged plain. L. Scadavay, on the lake-strewn moorland of North Uist, is said to have 365 bays and arms, and a further subsidence of about 60 ft. would convert it into a fiard and North Uist into many islands and a maze of sea channels.

The network of lochs in Harris and southern Lewis is quite dissimilar, and it consists of valleys of two different kinds and ages. Lower L. Seaforth and L. Claidh cut through the mountains of Harris and both trend roughly about N.N.W. to S.S.E. Further W. young steep-sided valleys that trend N. and S. also intersect these mountains; they include Glen Laxadale E. of Tarbert, the strikingly fiord-like Glen Meavaig—which is about 2000 ft. deep, between summits of 2265 ft. and 2392 ft., and would be converted by a submergence of 300 ft. into a sea-

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loch like L. Seaforth—and further W. the similar but less regular Glen Ulladale. The second series of valleys in Harris and South Lewis runs approximately E. to W.; this series includes L. Sealg in line with which, on the western side of L. Seaforth, is Glen Vigadale; further N. extending across the island is a series of lochs and valleys beginning on the W. with L. Resort and continuing through the middle section of Langabbat, the upper part of L. Seaforth and its tributary L. Sgibacleit, and ending across a low divide in Loch Odhairn on the eastern coast. Still further N. is L. Erisort. These E.–W. valleys are strikingly different from the meridional valleys. L. Erisort lies in a broad open old valley, which has been worn into its present form by long continued denudation; it is a gutter valley—not a fiord valley.

The age of the E.-W. valleys is post–volcanic because, as shown at L. Skiport, they are later than the dykes. Several dykes are marked on the maps of Prof. Jehu and Mr. Craig. We noticed others, but only on the lower ground. Their absence from the summits and higher ridges suggests that the Outer Hebrides were on the edge of the area reached by the dykes, so that they died out at greater depths. The loch valleys are post-volcanic but pre-glacial.

The possible formation of the valleys across the Outer Hebrides by rivers rising from the Minch has to be considered. This origin appears inconsistent with the eastward slope of the summits; they were part of a plateau which drained to the Minch. The slopes of the existing spurs both in North and South Uist show that the mountain range formed the divide between rivers flowing westward and those going eastward into the Minch.

### Disruption and Reversal of the Primary River System.

The E.–W. valleys belong to two generations and most of them were later than the great peneplane to which Scotland was reduced after the volcanic period. These valleys are part of the E.–W. geographical features that are widespread through north-western Europe. The earlier Scottish E.-W. valleys were probably Upper Miocene in age; the later series were probably about Middle Pliocene.[1] The drainage from the Forest of Harris then flowed to the Minch and the Atlantic through these gutter valleys; one of

[1] The evidence for these dates is stated in a paper on the Fiords of the Hebrides, *Geogr. Journ.*, vol. lxix, 1927, pp. 193-216.

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the rivers from the Cearnabhal Ridge (which is E. of Langabbat) flowed eastward through Upper Loch Seaforth into L. Odhairn, and another further N. flowed into L. Erisort. Subsequently the formation of the N.–S. valleys diverted much of the drainage of the northern slopes of the Forest of Harris southward through L. Seaforth, Glen Meavaig and the parallel valleys. Thus the primary E.–W. drainage of Harris and Southern Lewis was broken up by the formation of meridional fracture valleys.

The disruption of the ancient river system of the Outer Hebrides may be seen elsewhere in the islands. In North Uist most of the present drainage is to the Minch, whereas it was doubtless formerly westward. The drainage from Eaval, to the S. of L. Eport, was also to the W., but it has been captured by L. Obisary, and carried eastward through L. Eport. That remarkable loch was probably formed along a fault which produced the long straight southern side, W. of the narrow bottle-neck entrance, whereas the northern side is deeply frilled and indented as the land was submerged by the downthrow.

In South Uist the surviving mountain slopes are to the west, while the eastern front rises steeply from the Minch. The longer spurs and ridges of South Uist descend westward, and they are separated by valleys which were no doubt due to the primary drainage of the island. One clear case of river capture and reversal in South Uist may be seen from the Boisdale Hills. At present L. Shuravat (S. on fig. 2), and L. Stulaval drain through L. a Bharp to L. Boisdale; just N. of L. Shuravat a wide low gap leads to the Hornary River and thus to the W. coast. The drainage of the L. Stulaval basin must once have gone through that gap to the Hornary and it has now been diverted to L. Boisdale. No doubt nearly the whole of L. Boisdale once drained westward, but the route was reversed when the valley of Outer L. Boisdale broke through the range of South Uist.

The direction of the fiords is the best clue to their cause. These valleys in the Outer Hebrides, as in the mainland, have four chief directions, E.–W., N.–S., N.W.–S.E., and N.E.–S.W. The E. and W. valleys are particularly conspicuous, for they have broken up a continuous island into the Barra Isles, form the southern coasts of S. Uist, the lower part of Lochs Boisdale, Eynort, and Skiport, L. Eport, and further N. Lochs Sealg, Erisort, Resort, Loch Bharraglom, which joins the inner ends of E. and W. Lochs Roag, the northern shores of E. L. Tarbert, the

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southern shore of W. L. Tarbert, and the numerous narrow lochs in central Lewis.

The N.–S. direction, which is that of S. Uist as a whole, is best developed in the valleys through the Forest of Harris, though Lower L. Seaforth and L. Claidh trend a little W. of N.

The predominant fiords are the N.W. to S.E. series, including the two Lochs Roag on the western coast of Lewis, the lochs on the eastern coast of Harris, the main direction of L. Maddy, Upper L. Skiport, and its continuation L. Bé, Upper L. Eynort, and many of the smaller southern sounds.

The N.E. to S.W. direction is that of Lewis; it occurs also in the northern end of L. Langabbat, in Broad Bay, the Eye Peninsula, and the middle part of L. Seaforth.

As has often been remarked the volcanic belt of the Western Isles including Mull, Ardnamurchan, Rum, Eigg, Skye, and the islands in the Minch, probably occurs along a sunken band for such is a frequent position for volcanic eruptions. The lavas apparently did not extend much further west, as the dykes are less numerous and there are no known volcanic plugs in the main chain of the Outer Hebrides,[1] though there are outliers in St. Kilda and Rockall and the Porcupine Bank (10° 20 ft. W., 53° 40′ N.). That the Minch was formed as a down-faulted area was suggested by Sir Halford Mackinder, who identified it as a submarine rift valley. (" Britain and the British Sea," 1902, p. 75). This origin of the Minch was also adopted by Heddle, in Harvie-Brown and Buckley, " Vertebrate Fauna of the Outer Hebrides," 1888, p. 228. This view is confirmed by three lines of evidence. The western peninsula of Skye consists of sheets of lava that slope gently eastward and end at the coast in abrupt scarps. This feature shows that these lava sheets rose higher to the W. and formed there either an anticlinal arch or wide plateau, and that the Minch was formed by down-faulting. The second indication is that the steep eastern front of South Uist represents the scarp formed as the western side of the sunken belt. Third, the columnar basaltic islands off Loch Maddy and Weaver Point are outliers of Skye.

The sea-lochs of the Outer Hebrides therefore fit in well with those of the Inner Hebrides and the mainland of western Scotland.

[1] Heddle (*op. cit.* p. 236) remarks that " the three Maddies " have " every appearance of being vents." Inspection as we sailed past showed nothing to support that conclusion.

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They are arranged on four directions which are correlated with the Alpine movements of the Oligocene and Miocene, and with the main tectonic lines in the north-east Atlantic. (*cf. Geogr. Journ.*, lxix, 1927, pp. 205-11). The E.–W. valleys and tectonic lines are the oldest connected with the fiord valleys and they are part of the geographical features in north-western Europe due to the Alpine foldings. Subsidences in the north-eastern Atlantic led to the volcanic eruptions in the Hebrides, and made fractures trending N.W. to S.E. which were injected by basalt. Subsequent subsidence to the north subjected northern Scotland to torsional stress along a N.–S. axis. This torsion fractured the foundation on intersecting diagonal lines trending north-westerly and north-easterly.

These movements were probably all earlier than the Middlle Pliocene, when a general uplift of the British region caused the gaping of the four lines of fractures. The clefts thus opened across the Outer Hebrides were widened by denudation into the valleys occupied by the main sea-lochs.

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No. III.—PRELIMINARY ACCOUNT OF THE POST-DALRADIAN GEOLOGY OF KINTYRE. By W. J. McCALLIEN, B.Sc., ASSISTANT IN GEOLOGY, GLASGOW UNIVERSITY.

(Read 14th October, 1926; issued 1st August, 1927).

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## PART I. SOUTHERN KINTYRE.

### PREVIOUS LITERATURE.

1819. MACCULLOCH, J: "A Description of the Western Islands of Scotland and the Isle of Man, etc."
1852. NICOL, J: "On the Geology of the Southern Portion of Cantyre," *Q.J.G.S.*, viii, pp. 406-425.
1864. HULL, E.: "The Raised Beach of Cantyre" *Geol. Mag.*, iii, No. 1, pp. 5-10.
1865. THOMSON, J.: "On the Geology of the Campbeltown District," *Trans. Geol. Soc. Glasgow*, ii, pt. 1, pp. 76-89.
YOUNG, J. WALLACE: "Analysis of Minerals from Campbeltown," *Trans. Geol. Soc. Glasgow*, ii, pt. 1, p. 89.
1898. PATERSON, J., and RENWICK, J.: "Report of a Visit to Sanda and Glunimore," *Trans. Nat. Hist. Soc. Glasgow*, v. pt. 2, pp. 201-203.

1. *District Described.*

Southern Kintyre comprises the district S. of the main road between Campbeltown and the northern end of Machrihanish Bay. The area is naturally divided into two parts: 1. S. of an E.–W. line through Campbeltown, Kintyre forms a rectangular area bounded to the W. by a straight and mountainous N.–S. coast, to the S. by a slightly concave shoreline running in a general E.–W. direction, and to the E. it ends off sharply in steep cliffs of O.R.S. 2. Between the E.–W. line through Campbeltown and the northern limit of the district is a triangular area of low ground covered with recent deposits.

This paper includes a description of the islands of Davarr and Sanda.

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2. *Topography.*

(*a*). *Coastline.* Two types of coast are remarkably well developed in Southern Kintyre:

(*i*). Long beaches of fine sand backed by raised beaches, river deposits, and sand dunes, and

(*ii*). Steep precipitous cliffs of metamorphic rocks and O.R.S. conglomerates rising in places to about 1,000 ft., within half a mile of the sea.

Machrihanish, on the W. coast, is by far the most important of the beaches, extending for 3½ miles in an uninterrupted stretch of sand. For about two miles on either side of Southend are the less extensive bays of Carskey, Dunaverty, Brunerican, and Polliwilline. The narrow neck of land separating Dunaverty from Brunerican Bay is a raised beach considerably modified by sand dunes. The characteristic headland of Dunaverty, which forms the southern extremity of this neck of land, is a mass of L.O.R. conglomerate, and was originally, at no very ancient date, an island separated from the mainland to the N.W. by the Conieglen Water, which then entered the sea in Dunaverty Bay. By the banking up of sand and gravel, and of raised beach deposits by the action of the waves and the tides, and by the work of the wind in forming sand dunes this neck has now been captured by the land, and the river has been forced to change direction and cut its way S.E. to Brunerican Bay. Similarly, the Breackerie Water has been deflected W. by the banking up of the shingle along the central and eastern parts of Carskey Bay.

The W. coast is bold and precipitous, especially at the S.W. corner (the Mull of Kintyre).

To the N. connecting Machrihanish and Campbeltown, is a broad fertile plain—the Laggan of Kintyre—running in a series of terraces from the Atlantic to within a mile of Campbeltown where the terraces give place to higher rounded knolls rising to a general height of 200 ft., and separated from each other by the highest raised beach. The chief platform in this plain is formed by the Machrihanish Water and its tributaries, the Backs and the Chiscan Waters, and, on both sides of this, we get the three terraces separating the 25-foot, 50-foot, and 100-foot raised beaches from each other and from the alluvial plain of the rivers. The 100-foot beach runs a considerable distance up the valleys leading to the higher ground to the north and south of the laggan. To the extreme W., 3½ miles of sand dunes, higher than the plain behind

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them, give slight protection to the greatest stretch of cultivated land in Kintyre. Near the centre of the plain is a circular peat moss known as the Durry Moss.

Raised beaches are well seen in other parts of the coast and in particular around Uisead (Machrihanish), from Campbeltown to New Orleans, at Southend, and from Cove Point to Polliwilline Bay.

Island Davarr, which guards the entrance to Campbeltown Loch, is composed chiefly of orthophyre. The development of the present shape of the island is interesting. To the E. and S.E. where it is exposed to the fury of easterly and south-easterly, and even southerly gales, it consists of perpendicular cliffs rising from a narrow platform at sea-level. Some fine examples of sea-caves are seen in this south-eastern part of the island. On the N.W. and W., however, where Davarr is sheltered by the mainland, the island slopes gradually down to the raised beach. (Fig. 11).

Fig. 11.—Davarr Island from Kilkerran Road, Campbeltown, showing steep south-eastern cliffs and gently sloping north-western shore.

(*b*) *Inland.* But for tracts of Carboniferous lavas, and small areas of Old Red Sandstone, the greater part of Southern Kintyre is mountainous. The mountains are not high (Cnoc Moy, 1462 ft., 4 miles S.W. of Machrihanish, is the highest), but they possess the boldness and wildness which is lacking in the northern part of the peninsula. The ruggedness of the high ground, except on Beinn Ghuilean, is hidden under an extensive covering of boulder clay.

The relations of the geological structure to the topography are everywhere admirably displayed, especially in the neighbourhood of Killellan, mid-way between Campbeltown and Southend. Here the O.R.S. deposits to the E. form a plateau, which, at the road, is overlain by Calciferous Sandstone lavas with characteristic terraced appearance so common elsewhere in the Firth of Clyde and Midland Valley of Scotland. The lavas are cut through by intrusions of "porphyrite"; and each intrusion, and the one which is surrounded by U.O.R. cornstones, is represented by an

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isolated knob-like hill. To the W. of the main road the high ground of metamorphic rocks rising from the Conieglen Water is pierced by the large basaltic dome of Cnoc nan Gabhar. In the Machrihanish district, instead of the usual escarpments, the lavas give a series of rounded hills rising to the bare rugged peaks of Skerry Fell Fad and Skerry Fell.

The conspicuous rounded hill of Cnoc Garbh, behind Machribeg farm, Southend, represents the remains of an O.R.S. volcanic vent piercing O.R. conglomerates.

3. *General Geology.*

(*a*) *Tabular View of the Rocks.*

*Recent and Post-Tertiary.* Peat, Boulder Clay, Blown Sand, Fresh Water and Marine Alluvium.

*Kainozoic.* Basalt, olivine dolerite, and crinanite. One dyke of monchiquite.

*Carboniferous.* Sediments, lavas, agglomerates, tuffs, and intrusive rocks.

*Old Red Sandstone.* Sediments, agglomerates, tuffs, and intrusive rocks.

*Pre-Cambrian Metamorphic Rocks.* Metamorphosed sedimentary and igneous rocks.

(*b*) *Pre-Cambrian.* To within two miles of Machrihanish Bay, the western and south-western portion of the southern extremity of Kintyre as far as Carskey Bay and Ballybrenan to the E. consists of Pre-Cambrian metamorphic rocks. These are composed chiefly of siliceous and micaceous schists, quartzites, phyllites, coarse and fine grits with blue quartz pebbles, green schists, epidiorites, and coarse black crystalline limestones.

A wedge-shaped mass of similar rocks occurs from Campbeltown south. The broad part of the wedge is along the southern shore of Campbeltown Loch from the town to Glenramskill, and the point lies between Tod Hill and Cockstane.

(*c*) *Old Red Sandstone.*

(1) *Classification.*

| | |
|---|---|
| Upper Old Red. | Conglomerates of Highland rocks, and sandstones. |
| | Cornstones. |
| | Red marly shales. |
| | Conglomerates. |
| | Red and white false- and current-bedded sandstones. |
| | Conglomerates. |

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Lower Old Red.
- Conglomerates of "porphyrite" and quartzite boulders.
- Conglomerates of "porphyrite" boulders.
- Agglomerates.
- Conglomerates of quartzite boulders.
- Basal Breccia.

(2) *Lower Old Red Sandstone.* These deposits rest directly upon tne schists of the district, and are well exposed in the shore and cliff sections from Keil Point to Dunaverty, Southend. The basal breccia is absent in this part of Southern Kintyre, and the section begins with gritty red and white sandstones with shale pebbles, red sandstones with grit bands, red marly shales followed by red micaceous sandstones and greenish felspathic sandstones. At Keil Point house there are bands of red and buff coloured shale with false-bedding. Gritty sandstones continue with the other varieties until, to the W. of the sea-caves, we find a band of coarse conglomerate which has weathered into a white calcareous mass. Here begin the conglomerates of rolled quartzite boulders, and the cliff section shows a series of faults, doubtless connected with the volcanic vents on the shore beneath. Many of the quartzite boulders are cracked and broken. This faulted area continues right up to the wall running from the road to the cliffs. On the shore below the road we find masses of quartzite-conglomerate and sandstone, 30 ft. or more in length, tumbled about in every direction, and yet in situ within the sandstones. They are associated with rounded pebbles and boulders of "porphyrite." It is here that the conglomerates of igneous rock boulders begin. Rounded, and sometimes angular boulders of such rocks are now found associated in an agglomeratic matrix with bands of finer agglomerate rich in biotite. Eastward we get alternate sandstones and agglomerates with sandy shales containing abundant infiltration products of silica. Within the agglomerates, boulders of agglomerate and "porphyrite" up to 4 ft. in length are common, and thin discontinuous bands of cornstone often indicate the bedding. Next comes a series of false-bedded sandstones and thin cornstones, and towards Dunaverty we get agglomerate, tufaceous sandstone, lenticular cornstones, and the more abundant conglomerate of rounded boulders of igneous rocks and quartzite.

The following is Geikie's description[1] of this section and of the two volcanic vents which were discovered by Symes on the shore at Keil.

[1] "Ancient Volcanoes," 1, 1897, pp. 312-313.

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"At Keil Point, a little to the east of the most southerly headland of the Mull of Cantyre, some reddish and purplish highly felspathic sandstones dipping towards the east are found to pass upward into coarse volcanic breccias, which followed eastward, lose almost all trace of stratification, and are then abruptly succeeded by a neck of coarse agglomerate measuring 25 yards from north to south, where its limits can be seen, and at least 12 yards from west to east. It is hardly possible to distinguish between the breccias to the west and the agglomerate of the neck, except by the rude bedding of the former which pass down into well-bedded sandstones.

. . . . . .

A few hundred yards further east a large neck rises on the beach immediately to the south of the Old Celtic chapel of St. Columba. It is about 125 yards broad from east to west, on which sides it is seen to be flanked by coarse volcanic breccias and conglomerates, resembling in composition the materials of the neck, but showing an increasingly definite stratification as they are traced eastward in the ascending succession of deposits. Following the section in still the same easterly direction along the coast, we find that bands of fine felspathic sandstone, marking probably intervals of quiesence, are again and again succeeded by coarse brecciated conglomerates of igneous materials, which may be inferred to have been due to a renewal of violent eruptions."

The above may be taken as a fairly typical section, and the eastern part of the district, from Glenramskill to Polliwilline, consists of practically similar rocks, with perhaps a greater development of sandstones and sandy shales connecting the rocks of Keil with those of the neighbouring island of Sanda.

Lower Old Red Sandstone also occurs in the rounded hills to the W. of Campbeltown, and in the area between Homeston and Killypole Loch.

The lowest member of this division, the basal breccia, is only seen in one or two places. Perhaps the most remarkable of these occurrences is that on the shore to the W. of Carskey Bay at Port na Cusaig. The coarse rock here reminds one of the fault breccia met with in other parts of the peninsula and is made up of irregular pieces of vein quartz, talc schist, and quartz schist, with many indeterminable fragments. There is a gradual passage from normal metamorphic rocks, through this breccia, to red fine grained sandstones.

Impure limestones occurring in the Lower Old Red have already been mentioned in the description of the Keil Point section, but they are of subordinate importance. An outcrop near the Lifeboat Station, Dunaverty, has now become covered up with sand. In the published one-inch map two outcrops of limestone are shown crossing Dunaverty Point in a direction from W. of N. to E. of S.

In this map, also, two intrusions of felsite are mapped on the

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shore of the mainland south of Davarr Island. The first is indicated to the E. of Kildalloig House and the other a little to the south of the basaltic dyke E. of Ballimenach. I have been unable to collect specimens of these intrusive rocks, but collected siltstones which were mapped probably as felsite.

The rock from below Kildalloig House is not unlike a compact banded igneous rock of a green colour, and it occurs among sandstones and fine agglomerates. As seen under the microscope its sedimentary and detrital nature is evident. It consists of clear bands of very micaceous sandstone, containing abundant angular grains of quartz, and sharply separated from bands of extremely fine brown shale passing outwards through a medium grained rock into more micaceous sandstone. White and brown micas are very abundant.

The Ballimenach rock is interbedded with hard sandstones and coarse conglomerates of igneous rocks, and consists, as does the rock from Kildalloig House, of sharply defined sandstones and shales, this time with much secondary calcite. The hand specimen is a normal brown mottled shale.

(3) *Geology of Sanda.* Since Sanda is composed entirely of L.O.R.S., its geology will be described at this stage.

Sanda is an island a little over 1½ miles from the southern coast of Kintyre, and about 1⅝ miles in length from E. to W. and ⅝ miles from N. to S. It is extremely wild and rugged. It rises in bold escarpments to a height of 405 ft., (fig. 12), and is given over entirely to sheep farming. The only dwellings on the island are those belonging to the farm and to the lighthouse. The latter is situated on Prince Edward's Rock or Ship Rock, to the S. This rock, which rises from sea-level to over 100 ft., is connected with Sanda by a narrow isthmus.

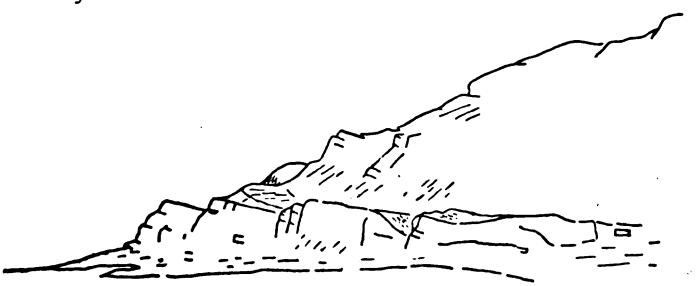

Fig. 12.—Headland E. of Sanda farm, showing escarpments of L.O.R.S. breccia.

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Around the island, and notably to the north-east, are numerous small islands, the largest of which, Sheep Island, is 500 yards in length and 132 ft. in height. Glunimore, south-east of Sheep Island, rises to about 50 ft.

As seen from the sketch (fig. 13), the eastern part of Sanda contains all the higher ground, and to the W. and separated from this part by a large fault, is a grass covered platform rising in gentle curves to 200 ft., and dropping sheer into the sea from about 100 ft.

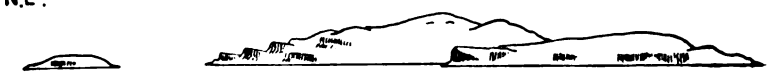


Fig. 13.—Sanda and Glunimore as seen from Dunaverty.

On the eastern extremity of Sanda there has been a great landslip and huge masses of breccia, grit, white and red sandstones, and subordinate cornstones have fallen from the cliffs above.

Raised beaches are admirably preserved around Fliuchach where we get platforms representing the three raised beaches of the mainland. Beach deposits rise a considerable height in the valley leading from Sanda Roads to Fliuchach. Elsewhere, however, only the 25-foot beach is preserved in the small recesses between the sea cliffs. Though in most parts of the island the coast is steep close-to, in many places, as E. and W. of Fliuchach, and to the W. of the Black Rocks, the points consisting of shales and sandstones run out for great distances in flat reefs with sharp bands projecting upwards where harder layers have resisted denudation better than the softer. (fig. 14).

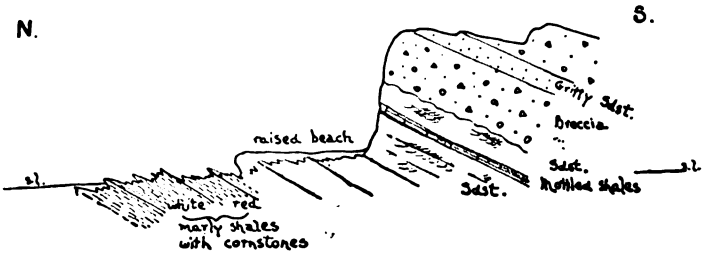


Fig. 14.—Diagrammatic section E. of Sheep Fank, Sanda.

A wonderful natural arch, about 80 ft. high and known as Elephant Rock, occurs to the E. of Sanda lighthouse. It shows a column of breccia, resembling the trunk of an elephant, passing

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into the main body of rock by little steps and it has been formed by the falling out of masses of rock from along the bedding planes and between joints at right angles to the strike. (fig. 15).

Sea-caves are abundant around the precipices forming the coast, and in some of them masses of calcium carbonate as bulky as a human being hang from the roof. In several instances the caves originated along faults, and in others at the eastern end of the island they have been cut out along the dip of the rocks.

As already stated, the island is roughly divided into two by a N.—S. fault. Each part is likewise intersected by a series of faults, and it will be found easier, in describing the rocks making up the island to describe separately each of the parts between faults, more or less parallel, and with a general direction from N. to S.

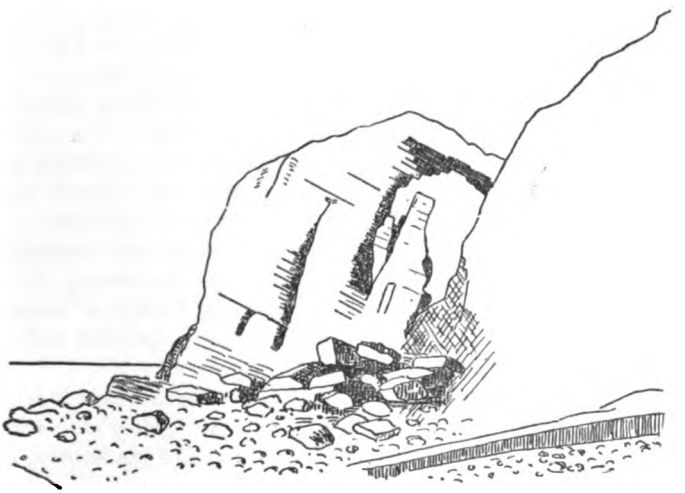

Fig. 15.—Elephant Rock, Sanda. A natural arch in coarse Lower O.R.S. breccia, E. of Lighthouse. The arch is roughly 80 ft. high.

(i). Beginning at the pier, we find white and red sandstones with shaly bands and bands of chocolate brown sandstone with nodules of limestone. At the cave on the first point to the W. of the pier there is a fault, the actual fault plane of which is seen for about 10 yards, covered with fault breccia. It inclines to the N. of E. at a steep angle. The dip of the rocks on the downthrow side is steeper than on the western side of the fault. There are



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numerous other small faults hading in different directions. Limestone boulders and pebbles of harder sandstone become common in the sandstones, and many of the latter weather into a network of hollows separated by harder ridges. Veins of calcite also run through the sandstones.

A little to the W. of the red perch a large fault inclining to the W. brings white sandstones and shales with cornstones against white and red sandstones. The cliff section from here consists of similar sandstones (with occasional pebbles of quartzite and shale), shales, and cornstones, and shows many apparent faults formed by the subsidence of sandstone into shales when the latter were not hard enough to support the weight.

At the top of this series, as seen at Fliuchach, we have greenish white and subordinate brown marly shales and sandstones. Overlying this are red sandstones and nobbly cornstones. The red sandstones are extremely false- and current-bedded, and not unlike the U.O R.S. to be described later. Above these again are conglomerates containing abundant quartzite, schistose grit, and igneous rock pebbles. Elephant Rock and Prince Edward's Rock consist of coarse breccia and gritty sandstone. The pebbles in the breccia are composed of quartzite, schist, schistose grit, vein quartz (the most abundant constituent), and igneous rocks (including quartz porphyry). E. of these rocks we get sandy and marly shales, quartz breccia, red sandstone, and cornstone, followed underneath by thick greenish white sandstones, shales, etc., similar to those W. of Fliuchach. A triangular mass of shales and sandstones is faulted between the main fault and the conglomerates to the E.

Returning to the northern shore and working eastward from the pier we get white micaceous sandstones, coarse gritty sandstones, and bands with abundant cornstone boulders, red sandstones, and subordinate marly shales.

(ii). Faulted against, and to the west of this series on the northern coast are thick deposits of conglomerates containing large rounded boulders of igneous rocks and yet deserving the name agglomerate in that they are nothing but the washed detritus of contemporaneous volcanic action. On the shore, and cut off to the W. by the main fault, is a rounded mass of agglomerate, 24 yards from E. to W., which from the absence of bedding is thought to be a small volcanic neck. Overlying the coarse volcanic conglomerates forming the vertical cliff of about 100 ft., at

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this point are greenish white sandstones, above which are more thick conglomerates of igneous rocks. After this section, within the coarse conglomerates we get a band of finely bedded red and greenish white sandstone, sharply overlying which is a thin continuous band 1 ft. 2 ins. thick of compact fragmental material, which on first examination resembles a sill, but for the fact that the upper junction with the conglomerates is not sharp. Within this conglomerate also, and not associated with sandstone, are bands and lenticles of cornstone about 1 ft. in thickness.

On the shore W. of Fliuchach we get white sandstones with lenticles of cornstone and coarser flaggy sandstones with brown sandy shales.

(iii) At the western part of this series of conglomerates on the northern coast [(2) above], the coarseness of the material diminishes, and sandstones become more frequent. In the slice of rock faulted along the shore by a N.-W.–S.-E. fault the chief rocks are sandstones, conglomerates of small boulders of igneous rocks, and mottled green and brown cornstones.

(iv). This includes that part of the island between the northern coast from the kelp store to the valley W. of the Black Rocks, and the southern coast from the bay E. of Fliuchach to near the south-eastern point of the island. Sections over the whole of this area are abundant.

In the escarpment behind the sheep fank in Sanda Roads we get gritty sandstones overlain by a thick breccia of quartzite, quartz, schistose grit, igneous rocks, and, at the base, many fragments of the underlying sandstone. Beneath this red sandstone are mottled marly shales succeeded by more red sandstone. On the shore north of the cliff, underlying the sandstones are bands resembling conglomerates with abundant small lenticles of cornstone (fig. 14). Faulted against these are mottled red marly shales with harder sandy bands projecting above them.

The high ground behind this and the slopes down to the southern coast are composed entirely of coarse breccia. This consists of pebbles similar to those obtained from Elephant Rock, and in one place E. of Fliuchach small agates were found to be fairly abundant

(v). To the E. of this series of sandstones, shales, and breccia above figured, comes another great series of breccia similar to that overlying the sandstones. It contains remarkably few large boulders, and, in the landslip mentioned in the introduction to the geology of Sanda, we find mottled shales and cornstones. But for this, the entire eastern end of Sanda consists of breccia.

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(4) *Upper Old Red Sandstone.* Unconformable upon the L.O.R.S., and often resting upon the metamorphic rocks without the intervention of the lower division, comes the U.O.R. This is strikingly different from the L.O.R.S. in that it consists of conglomerates of quartz pebbles (with fewer fragments of quartzite, grits, and schists), false- and current-bedded red (and subordinate white) sandstones, thick bands of cornstones of a whitish colour but often tinged with red and purple, and red marly shales. An admirable section across this group is afforded by the Southend shore from the Little Clet to the point E. of Rudha McShannuich. The upward succession, which is the direct continuation of the Keil section of the L.O.R.S. already described, is given by the following description of the coast line.

The Little Clet consists of conglomerates of Highland rocks, and of white sandstones.

The Big Clet is similar, but with a greater development of red sandstones.

The next point to the E. is made up of false- and current-bedded red sandstones with subordinate conglomerates and white sandstones.

Rudha McShannuich begins with white sandstones and thin calcareous bands to the W., followed by red mottled sandstones, and a broader band of impure sandy limestone overlain by almost horizontal conglomerates.

Innean Mor, separated from Innean A'Chromain by a fault, consists of red marly shales, while overlying these, and forming the next headland to the E. is a thick band of cornstone with distinct columnar structure, the columns being surrounded and separated from each other by pale greenish sandstone.

As seen here, a coarser quartz conglomerate forms the top of the U.O.R.S.

All these rocks dip to the E. becoming almost horizontal E. of Rudha McShannuich.

In the one-inch map a dip mark in about the position of the Big Clet, indicates an inclination to the W., but this has been obtained from rocks which are not in situ.

U.O.R.S. rocks occur in Polliwilline Bay dipping towards the S.W. and representing a continuation of the above section. They are met with also at Killellan and Kilwhipnach, where cornstones are remarkably well developed.

Tomaig Burn, Killeonan Burn, and Chiscan Water, all running right across that narrow belt of U.O.R.S. which surrounds the Carboniferous lavas of the central part of Southern Kintyre, give fairly continuous sections, though thick deposits of boulder clay often obscure the bed-rock. The following are tabular representations of these sections, from W. to E. in descending order.

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| *Tomaig Burn.* | *Killeonan Burn.* | *Chiscan Water.* |
|---|---|---|
| Carboniferous lavas. | Lavas. | Lavas. |
| Quartz conglomerate. | Red sandstone. | White pebbly sandstone. |
| Cornstone. | Cornstone. | Cornstone. |
| Shale with nodules of cornstone. | | Gritty Sandstone. |
| Cornstone. | Cornstone. | Cornstone. |
| Red and white sandstone. | | |
| Cornstone. | | |
| Shale. | | |
| Red and white sandstone. | | |
| | Red sandstone with brownish cornstone. | Red sandstone. |
| Intrusion of "porphyrite." | | |
| Schist. | Schist. | Schist. |

The schists in the above table are separated from the younger rocks by a N. and S. fault, which in Tomaig Burn is coincident with an intrusion of "porphyrite."

A splendid section of the U.O.R.S. occurs in the cliff section S. of Uisaed, Machrihanish. The section begins at a small promontory S. of Eudan nan Gallan and stretches to the S. of the cliffs known as the Galdrings (or Cauldrons). From here, the strike of the rocks carries them S. of the main road E. of Ballygroggan.

In the Galdrings thick massive cornstones, with sandstones and conglomerates, rest directly upon the schists and end off to the S.W. against a bank of similar rocks. The cornstones are overlain by Carboniferous lavas from which they are separated by

brown sandstone (1 ft.), containing cornstone (2 ins.)
red marly sandstone (8 ft.)

Though cornstone is the chief rock of the remainder of the section, we get bands of red and white marly shales, sandstones, and conglomerates.

In the one-inch map cornstone is shown occupying the cliffs only, with another broad band a quarter of a mile S.E., but the fields between these localities are of similar material (fig. 17 and 18).

(*d*) *Carboniferous.* Overlying the Upper, often upon the Lower O.R.S., and sometimes upon the metamorphic rocks comes the Carboniferous, beginning with lavas, followed by tuffs and agglomerates, and the Carboniferous Limestone Series of white sandstones, fossiliferous limestones, and coal seams.

The lavas occur in the basin at the S.E. corner of the area, and in the N.W. from Machrihanish to Killellan. Overlying the lavas south of Drumlemble, and exposed in the small burn running north

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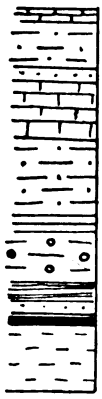
from Torchoillean, are tuffs, sandstones, coals, and fireclay with plant remains. Exposures are few. On the shore S.W. of the mouth of Machrihanish Water, and near low water mark, are isolated masses of sandstone and fossiliferous limestone, which, as I point out later, I believe are separated by a fault from the lavas to the south.

(1) *Tirfergus Burn.* The largest and most continuous section of this division is that which has been let down between E. and W. faults along Tirfergus Burn. Here, beginning at the "B" in "Burn" (6 inch sh. cclvii, S.W. Argyll), we get alternate thick bands of sandstone and limestone with associated black shales. The sequence is then interrupted by an intrusion of markle basalt, after which are more limestones followed by red tuffs with bands of quartz conglomerates. The next cliff sections are composed of sandstone, and several bands of limestone alternating with thin coals. The last limestone is succeeded by thick deposits of black shales and sandstones with plant remains, limestone, bright red marly shales, conglomerates, and gritty sandstones, with more limestone and, finally, separating these sediments from the lavas below, are thick tuffs and agglomerates. All these rocks dip down the stream.

The following is the above section after Thomson (from the work already quoted).



Limestone.
Gritty Shale.
Sdst.
Impure limestone.

Arenaceous shale (17 ft.).

Shale, Sdst.
Arenaceous shale with ironstone nodules (10 ft. 6 ins.).
Sdst, coal and bituminous shale.
Impure coal (17 ins.).

Indurated Sdst.

An open adit occurs on the river bank opposite High Tirfergus where a seam of fairly good coal, 4 ft. thick, was once worked. Thin seams of 4 ins. and 5 ins. with limestone overlie this. The

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tuffs and agglomerates or conglomerates of large rounded lava boulders end off sharply against the lavas.

It is impossible to study the Tirfergus Burn section in the summer as the best sections are entirely overgrown.

(2) *Machrihanish.* So far I have been unable to examine the Carboniferous of the Machrihanish hollow. The following tables represent two sections of the Wimbledon Shaft at the Argyll Colliery taken (1) from the Geological Survey map (sheet 12) and (2) from R. W. Dron " The Coal-Fields of Scotland."

(1).

| | | fm. | ft. | in. |
|---|---|---|---|---|
| | Superficial deposits | 5 | 3 | 6 |
| | Strata .. .. | 4 | 3 | 4 |
| 1 | Foul Coal .. .. | | 3 | 3 |
| | Strata | 5 | 0 | 3 |
| | Kilkivan Coal .. | | 1 | 10 |
| 2 | Coal Strata .. | 1 | 1 | 5 |
| | Coal .. | | 3 | 7 |
| | Strata .. .. | 2 | 4 | 10 |
| 3 | Coal .. .. .. | | | 11 |
| | Strata .. .. | 13 | 2 | 9 |
| | Coal .. | 1 | 1 | 6 |
| | Fireclay .. | | | 2 |
| 4 | Main Coal .. | | 4 | 3 |
| | Coaly blaes | | | 8 |
| | Coal .. | | 3 | 6 |
| | Coaly blaes | | | 8 |

(2).

| | | fm. | ft. | in. |
|---|---|---|---|---|
| | Surface and strata .. | 10 | 0 | 10 |
| | Coal (foul) .. .. | | 3 | 3 |
| | Strata .. .. | 5 | 0 | 3 |
| | Coal .. .. .. | | 1 | 10 |
| | Strata .. .. | 1 | 1 | 5 |
| | Kilkivan Coal .. | | 2 | 2 |
| | Strata | | 5 | 10 |
| | Seam Coal .. | | 3 | 7 |
| | Strata .. .. | 2 | 4 | 10 |
| | Coal .. .. .. | | | 11 |
| | Strata .. .. | 13 | 2 | 9 |
| | Main Coal .. | 1 | 1 | 6 |
| | Coal Fireclay parting | | | 2 |
| | Seam Coal .. | | 4 | 3 |
| | Coaly blaes .. .. | | | 8 |
| | Coal " Underfoot" (inferior) | | 3 | 6 |

(*e*) *Recent and Post-Tertiary.*

(1) *Raised Beaches.* These have already been described under Topography and consist of the three commonest types. The height of any one beach, however, is not constant and the following are the chief variations—the 25-foot beach, from the lowest raised beach up to 40 feet; the 50-foot beach, from the 25-foot platform to 60 feet; and the highest slopes from 60 feet to 100 feet.

Thick accumulations of the remains of *Lithothamnium* are remarkably abundant at Dunaverty, Southend.

(2) *Freshwater Alluvium.* The following is the section of alluvium seen in the Machrihanish Water at the bend between the mouth of the river and the Argyll Colliery.

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| | ft. | ins. |
|---|---|---|
| Coarse gravel .. .. .. .. | 5 | 0 |
| Black woody peat .. .. .. | 0 | 6 |
| Fine yellow stained sand .. .. | 1 | 5 |
| Thin parting of white sand .. .. | – | – |
| Gravelly sand .. .. .. .. | 0 | 6 |
| Fine (stained) sand .. .. .. | 0 | 5 |
| Gravelly sand .. .. .. .. | 0 | 5 |
| Fine sand .. .. .. .. .. | 0 | 7 |
| Gravel .. .. .. .. .. | 0 | 3–7 |
| Sand and scree .. .. .. .. | – | – |

To the west of the above section, where the steep face fades away, we get, among alternate coarse and fine gravelly bands, 2 ins. of coaly soil passing into 4 ins. of peat with well preserved plant remains.

A sample of black sand from the mouth of the Conieglen Water, Dunaverty, and derived from the O.R.S. contains garnets, zircons, pyroxenes, quartz, felspar, and abundant magnetite.

Nicol, describes several sections of the unconsolidated deposits of the Laggan of Kintyre. The lowest of these is a mass of red clay and upon this rests thick shingle banks of sand, gravel, and rounded boulders. In the hollows between boulder clay hills are large accumulations of peat with fine clays and sands, and these beds are thought to be of lacustrine origin.

(3) *Peat.* A glance at the one-inch geological map shows the abundance of peat bogs, and the peat is abundantly used for fuel. The amount of peat, unfortunately for the geologist, is greatly in excess of what is shown on the map.

(4) *Glacial Deposits.* Thick deposits of bright red boulder clay cover much of the high ground and fill most of the glens, where they have been cut through by the present rivers and burns. Boulders from the till consist chiefly of metamorphic rocks, Arran granite, and Drumadoon quartz-porphyry. Boulders of the Arran rocks have been found everywhere in Southern Kintyre and to the extreme S. of Sanda. Small boulders of Ailsa Craig paisanite were found on the beach at the Galdrings, Machrihanish. The glacial striae indicate a general E.–W. direction for the ice movement.

The author hopes to make a further study of the glacial geology of Kintyre.

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4. *Tectonics.*

(*a*) *Faults.* Naturally, the most interesting structural problems in Kintyre are those connected with the metamorphic rocks and therefore outside the scope of this paper, but a study of the younger rocks and their structures is of interest. It has often been asserted that Kintyre possseses the south-western continuation of the Highland Boundary Fault. To correct this common error a study of the faults occurring in the area at present under consideration is necessary. I have given local names to the most important faults and since these run in three directions, (1) N.W.–S.E. (2) E.–W. (3) N.–S., they will be described under this direction-classification (fig. 16).

N.W.–S.E. The *Kilkenzie* fault runs from Campbeltown Loch along the Campbletown-Tarbert road to South Ballivain where it crosses the sand dunes of the Machrihanish Links and enters the sea. To the N.E. of this line (the northern limit of Southern Kintyre) is the high ground of the northern part of the peninsula composed of metamorphic rocks with a few outliers of Palaeozoic sediments and lavas. S.W. of the main road is the great series of terraces of marine and fresh-water alluvium with rounded hills of Lower and Upper O.R.S. and occasional exposures of Carboniferous lavas. This fault is continued south-eastward over Trench Point and through Kildalloig Bay.

The *Drumlemble* fault runs from Oatfield House, near the Campbeltown-Southend road, to the shore of Macrihanish Bay S.W. of the mouth of the river. The sediments on the shore there, are, therefore, believed by the writer to be faulted against the lavas. South of Drumlemble, Carboniferous limestone sediments are brought into contact with lavas. This fault separates the high ground south of the Laggan of Kintyre from the laggan itself.

The *Polliwilline* fault is somewhat irregular in its course and begins in a north-westerly direction between Upper and L.O.R.S. on the shore of Polliwilline Bay, runs through L.O.R.S. rocks and finally in a W. of N. direction, separates the V-shaped mass of metamorphic rocks south of Campbeltown from the L.O.R.S. to the W.

Likewise the *Macharioch* fault begins as a N.W.–S.E. fault throwing Carboniferous lavas against U.O.R.S. cornstones. W. of Macharioch the fault follows a more westerly course.

The most westerly fault on Sanda runs in a N.W.–S.E. direction and many small faults also belonging to this group occur on the

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eastern coast of the mainland south of Achinhoan Head, and two cut across the lavas and U.O.R. sandstones and cornstones E. of Achnaclach, Killellan.

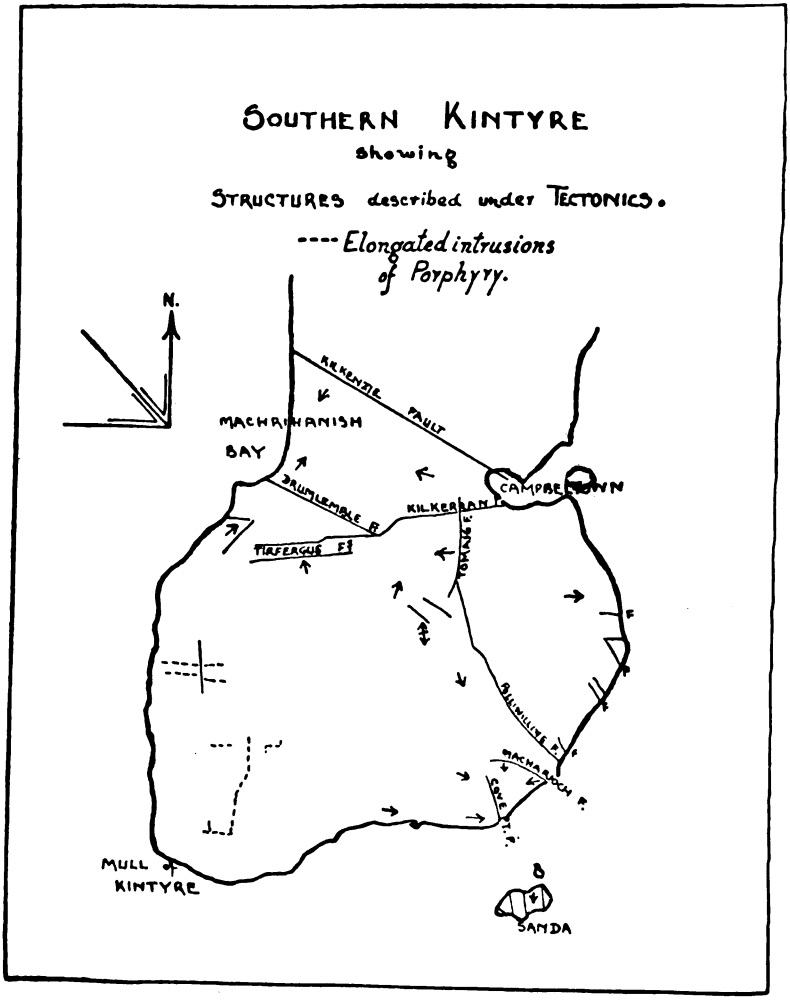


Fig. 16.

*E.–W.* The line of the *Kilkerran* fault is remarkably evident from the road W. of Davarr House where, looking westward we

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see right up the V-Shaped valley of Kilkerran on the lower slopes of Beinn Ghuilean. At the head of the glen is the elongated reservoir of Crosshill, also along the fault.

In the lower part of the glen the fault separates the Kilkerran porphyry from the Beinn Ghuilean schists; higher up schists with thick bands of cyrstalline limestone occur on the northern side of the reservoir and schists only on the southern side. Further westward L.O.R.S. rocks underlain by schists are separated from Carboniferous lavas.

The two *Tirfergus* faults on either side of Tirgerfus Burn let a mass of Carboniferous Limestone sediments down into the heart of the lavas. Killypole Loch lies in the line of the southern fault where the lavas occur against the L.O.R.S. The most northerly of the two faults may be connected with the Kilkerran fault.

Small E.–W. faults are found with N.W.–S.E. faults on the eastern shore of the mainland.

*N.–S. Tomaig* fault runs from Tomaig cottage, W. of Crosshill reservoir, to a point half a mile S. of Chiscan Water and separates bright red sandstone of the L.O.R. from metamorphic rocks. To the N. its place is taken by an intrusion of porphyry.

*Cove Point* fault has a direction slightly W. of N. and cuts through the Carboniferous Lavas, Upper and L.O.R.S. It is well exposed on the shore at Cove Point, where, E. of the lavas, are U.O.R. sandstones and quartz conglomerates. At Kilbride an old quarry has been worked in cornstone, while immediately to the E. are exposures of lava. Similarly the U.O.R. is brought into contact with the Lower.

The *Largiebann* fault cuts across green schists, quartz schists, epidiorites, and porphyry.

In the Geological Survey one-inch map there are four distinct faults shown on Sanda and though in the description of the rocks of Sanda five portions of the island lying between faults have been described these faults in several cases are slightly different from those in the published map, and are not indicated in it.

For instance, a fault is described in the present paper (p. 51) but it is not the fault taken as separating two sections of the island or two different sequences of rocks. Instead, the main fault is taken to the W. of the fault shown in the one-inch map and is bounded on one side by coarse conglomerates and on the other by sandstones.

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Similarly the fault separating (iv) from (v) (p. 51) is inserted E. of the low flat point, between breccia to the E. and sandstones and shales to the W. A smaller fault is described to the W. of this point within the shales.

A small fault connected with the main N. and S. fault through the centre of the island is described E. of Fliuchach.

(*b*) *Relation of Intrusion to Faulting.* Doubtless closely connected with these fractures in the earth's crust are the long stringer-like intrusions of porphyry which occur in Southern Kintyre, running in the two general directions, N.–S., E.–W. For example, we get the series of intrusions at

1. Largiebann, in the Strone district, and at Pennygown running in an E. and W. direction.
2. From Glenadale Water to Borgadel Water a N. and S. intrusion ending in an E. and W. branch and,
3. N. and S. intrusions N.W. of Glenmucklach, and one S. of Tomaig cottage.

This last intrusion is interesting in that it occurs along the line of the Tomaig fault and separates metamorphic rocks from U.O.R.S. For this reason it seems to me to *be contemporaneous with the N. to S. faults.* This porphyry is similar to the others of Lower Carboniferous age cutting through the Carboniferous lavas. The faults also cut through the lavas and Carboniferous Limestone Series. The arrangement of the main intrusions of this age in directions at right angles to each other indicates the close relation between the igneous activity and the faulting at the end of Lower Carboniferous times. In this connection mention may be made of a similar dyke which I have discovered running along an E. and W. fault at Largiemore in Northern Kintyre.

The crinanites and other N.W.–S.E. dykes, the basalt bosses and some of the sills are of Tertiary age and connected with the N.W.–S.E. faults which belong to the same period.

Thus it will be seen that the Laggan separating Northern Kintyre from the high ground to the S. and running from Campbeltown Loch to Machrihanish Bay, is of Tertiary age, as was first suggested by Bailey.[1] But the presence of the sedimentary rocks and lavas on the southern flanks of Northern Kintyre and on the northern slopes of Southern Kintyre seems to indicate that lower ground occupied this part from a much earlier time.

[1] "The Structure of the South-West Highlands of Scotland," *Q.J.G.S.* lxxviii, pt. 2, p. 103.

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(*c*) *Structure of the Palaeozoic Rocks.* The O.R.S. and Carboniferous rocks described in this paper occur in the outer portion of the quadrant of a circle the centre of which is composed of the metamorphic rocks of the high ground of the south-western corner of the area. That is, they were laid down in the lower ground surrounding these mountains and occupy a belt of country running in a N.W.-S.E. direction and to the S.E., bending southward. The structure of the rocks is comparatively simple though complicated in places by the faulting above described. The central part of the belt, and more or less the divide between the low ground of Machrihanish and the valley of the Conieglen and the low ground of Southend-Polliwilline, is composed of an anticline of L.O.R.S. passing N.W. to the basin of Machrihanish and S.E. to the corresponding basin, which for convenience has already been called the Southend basin, though it occurs somewhat E. of the village of that name. These have been described in the course of the present work and from the descriptions we see that the Southend basin is composed of Carboniferous lavas in the centre round which curve the U.O.R. rocks with conspicuous cornstone bands and underlain by a great thickness of L.O.R. deposits. The Machrihanish basin is somewhat complex in structure, due no doubt to the Tirfergus and Drumlemble faults and also to the unconformable nature of the deposits themselves.

Thus the Lower and U.O.R. dip N.E. on the S.W. slope of Tirfergus Hill and are overlain by the lavas forming the top and northern slope. At Killellan the lavas overlap the intermediate deposits and rest directly upon the metamorphic rocks. Cornstones and sandstones reappear E. of the main road and after running E. for some distance bend to the N. and follow the lavas up to the Kilkerran fault.

At the Galdrings, U.O.R. cornstones dip N. and N.E. under the Carboniferous lavas which soon overlap them as before.

The structure of the Palaeozoic rocks in the hollow between Machrihanish Bay and Campbeltown is obscured by superficial deposits but outcrops of lava, followed N.E. by O.R.S. at Kilkenzie, indicate the northern side of the basin, and the L.O.R.S. at Campbeltown indicates its eastern margin. The centre of the Machrihanish basin is filled with Carboniferous Limestone sediments which are absent from the mainland part of the Southend basin, though it is possible but unlikely, that they may outcrop beneath the sea to the S.E.

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The L.O.R. of the eastern part dips constantly E. except where it has been disturbed by small faults.

In few places can sections of unconformities and overlap be better illustrated than in Southern Kintyre. The L.O.R. is composed at the base of breccia of the rock immediately beneath it and occurs in hollows in these rocks. As the minor irregularities

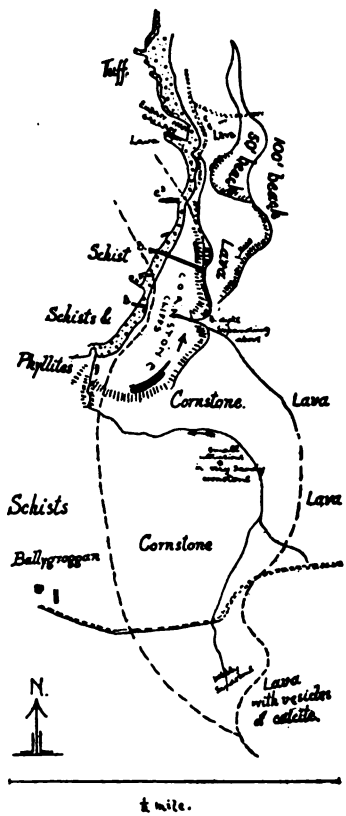


Fig. 17.—Detailed Geological Map of the Galdrings, Machrihanish.

in the very uneven surface of the Pre-Cambrian schists became filled in, more continuous sedimentation took place resulting in the formation of thick sandstones and conglomerates and the whole of the deposits are unconformably overlain by the upper division of the O.R. At the Galdrings, moreover, the U.O.R.S.,

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represented by a great thickness of cornstone, rests immediately upon a platform of schists and ends off against a steep slope of similar rocks (figs. 17 and 18).

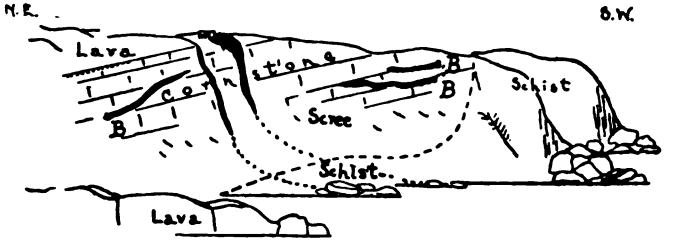


Fig. 18.—Diagrammatic sketch of cliffs from the Galdrings to Leac Bhuidhe, Machrihanish.

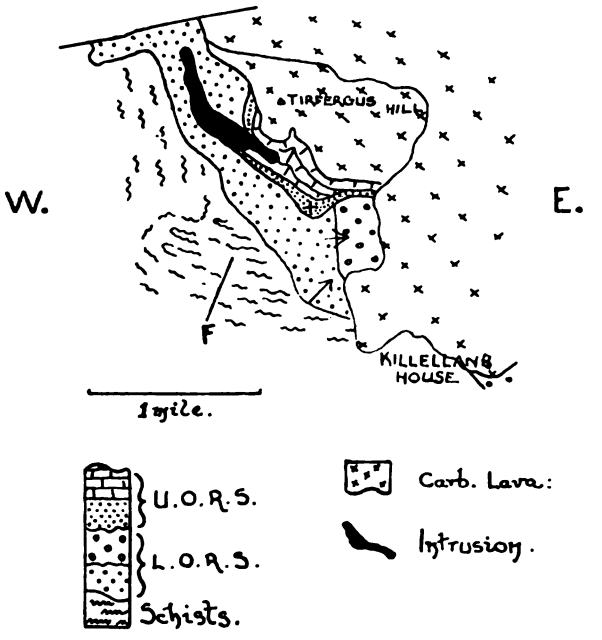


Fig. 19.—Sketch map showing unconformities and overlaps in the area N.W. of Killellan House.

Again, unconformable upon the U.O.R., are the Carboniferous lavas which, as they spread over the district and met with higher

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ground, came to rest upon the L.O.R.S., and finally upon the metamorphic rocks (as to the S.W. of Skerry Fell Fad and to the N.E. of Cnoc nan Gabhar).

The unconformity between the Upper and L.O.R.S. is seen in the Southend area, and complicates the structure of the district around Homeston, W. of Killellan; that between the Carboniferous and O.R.S. is illustrated by the Galdrings cliff section, and is well shown by the mapping of the thick band of cornstone W. of Kilwhipnach and of the Galdrings cornstone S.E. of Ballygroggan (Losset area).

All three unconformities are seen in the small area W. and N.W. of Killellan, between Kilwipnach and Glecknahavill. First to the W. are black crystalline limestones and epidiorites belonging to the Dalradian schists and striking E. and W. These, when followed E. are lost under L.O.R. conglomerates striking obliquely across them, or from N.W.–S.E., and these in turn are covered by sandstones and cornstones of the U.O.R.S striking more E. and W. than the conglomorates. Finally the Calciferous Sandstone lavas cut across the U.O.R.S. on to the L.O.R.S., and then across this till they rest upon the schists near Cnoc nan Gabhar (fig. 19).

(*d*) *The Highland Boundary Fault.* In other parts of this paper I have compared Kintyre with various areas in the Firth of Clyde and Midland Valley of Scotland, and the close resemblances between the geology of these areas and that of Kintyre suggests that we could easily link up Kintyre with Arran, Bute, and the mainland east of Bute. In doing so we cross the Highland Boundary Fault.

Let us look at the Boundary Fault in the different districts.

The general trend of opinion at the present day seems to be that the Highland Boundary Fault in S.W. Scotland is a great fracture throwing U.O.R.S. and even Calciferous Sandstone lavas down through a great distance until they now rest side by side with the Dalradian schists. The direction of the Highland Boundary Fault where it is known is roughly N.E.–S.W.

*Bute.* It is a well established fact that a fault occurs in Bute and divides the island into two, with a valley of low ground along the general direction of Loch Fad from Rothesay Bay to Ardscalpsie Point.

In Bute the most interesting point in this connection is that the Lower Carboniferous rocks occur against the schists. Therefore it is concluded that the Boundary Fault in the island is of post-

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Lower Carboniferous age. In the North Arran memoir it is stated that the Boundary Fault in Bute has a large and variable downthrow.

Immediately on the northern side of the fault in Ardscalpsie Bay is an interesting outlier of O.R.S., the Haystack, which rests directly upon the metamorphic rocks and which is composed of debris derived from these rocks. From what I have seen of similar material in Kintyre I would agree with the Survey in believing that the Haystack is composed of L.O.R. breccia but Mr. P. Macnair is of opinion (*Trans. Geol. Soc. Glasgow*, xvii, i, 1919-22, p. 109), that it belongs to the upper division of these rocks. This outlier leads me to believe that there is an even closer analogy between Bute and Kintyre than one would imagine from previous descriptions. It is my opinion also that the Highland Boundary Fault in Bute has a comparatively small downthrow. True, it faults Calciferous Sandstone lavas against metamorphic rocks but to do that in Kintyre would require no very important fault since in many places where the lavas are actually in situ they have overlapped the underlying rocks and rest directly upon the schists.

It is interesting to note that Dr. Davison in his "History of British Earthquakes" (p. 118), states that the fault which passes just to the S. of Dunoon and through Rothesay is a *branch* of the main Highland Boundary Fault, and Peach and Horne were of the same opinion (Map p. 448, *Bath. Surv. Scottish Fresh Water Lochs*, I, 1910).

*Arran.* The search for the Highland Boundary Fault in Arran is rather difficult for various reasons. That there exists a fault between the O.R.S. and the schists is proved in one or two cases but that it is a minor fault seems evident. Moreover, there are in the north-eastern part where we would expect to find the Boundary Fault a great many faults which let Carboniferous rocks down against schists and therefore closely resemble the Ardscalpsie fault in Bute. Other faults closely associated with these in Arran bring Permian sandstones against the metamorphic rocks. To me it seems that all these faults are directly connected with the intrusion of the Tertiary granite.[1] On the shore of Loch Ranza the Dalradian schists are unconformably covered by Lower Carboniferous calcareous red sandstones.

[1] Since this was written a paper by E. B. Bailey describing the structure of North Arran appeared in the *Geol. Mag.*, LXII, 1926, pp. 481-495.



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Stark, in a paper[1] (summary) on the "Highland Boundary Fault in Arran," states that "the Highland Boundary Fault strikes the north-east coast of Arran near the Fallen Rocks, where instead of continuing its normal south-westerly course, which would take it right across the granite mountains forming the nucleus of the island, it turns to the south and south-east, and describes a semi-circle concentric with the granite, till it disappears under the Sound of Kilbrannan at Dougrie. Here the fault appears to resume its normal direction, reappearing near the Mull of Kintyre, and passing on into the north-east of Ireland."

Later he states (p. 293) that the granite was intruded nearly or quite on the line of the Highland Boundary Fault and that it "forced up with it the schists which underlay the Old Red rocks on the south-eastern side of the fault and stretched and shifted them towards the east, compelling the line of the fault to shift with them, and take up a new direction concentric with the disturbing granite."

That is, though Stark's Highland Boundary Fault is running in an unusual direction in its course across Arran it resumes its normal trend under the waters of the Kilbrannan Sound, reappearing somewhere in Kintyre. But we want to know where it is found here and what Stark means by "near," and in what direction it is running "near the Mull of Kintyre."

Evidently Stark calls this the Highland Boundary Fault because it separates metamorphic rocks from O.R.S.

*Toward Point.* Perhaps one of the cases most often referred to in connection with the Highland Boundary Fault is the Toward Point occurrence in the Firth of Clyde. Here[2] red sandstones, breccias, and cornstones, representative of the U.O.R. rocks in general, abut against the schists from which they are separated by a great zone of crushed rocks and serpentine. No doubt the erroneous impression of the magnitude of the fault at this place is increased by the presence of the serpentine at the junction of such widely different rocks as red sandstone and phyllite.

The serpentine, however, is of the same age as the folding and metamorphism of the district of Cowal and that at the latest is pre-Upper Palaeozoic. The reasons for this statement are

[1] *Trans. Geol. Soc. Glasgow*, xii, 3, pp. 292-3.
[2] "The Geology of Cowal," *Mem. Geol. Survey, Scotland*, 1897.

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The outcrop of the serpentine is roughly parallel to the foliation of the schists. It cuts across it at one place (180 yds. S. of Innellan pier).

The schists are hardened and altered by the serpentine (or the rock from which it is derived).

The serpentine is schistose.

Serpentine occurs miles from the Highland Boundary Fault at Glendaruel.

The serpentine is supposed to be derived from an intrusion of sill-like character, and this intrusion was of considerable size.

If the O.R.S. were thrown down by a great fault then, we should expect the sandstones to be much more disturbed near the fracture. But they are lying almost horizontally and unaffected right up to the fault.

Fragments of O.R.S. rocks would be met with in the fault-breccia. No such fragments have been found.

It seems to me that the only evidence that faulting is responsible for bringing the Toward sandstones into their present position is that (*a*), different horizons of the U.O.R., cornstones in one place, red breccias in another, seem to be in contact with the same horizon of schists, and (*b*), the rocks close to the schists contain fewer schist fragments than one would expect if they represented basal members of the series. From my study of similar rocks in Kintyre I conclude that (*a*) has practically no weight for the faulting hypothesis, as the irregular nature of the floor upon which the O.R. rocks were laid down is a sufficient reason for overlapping such as we have here. Further, it is difficult following horizons in the schists. (*b*), on the other hand, is more reasonable, but in parts of Kintyre, e.g., at the Galdrings, U.O.R. cornstones with sandstones and conglomerates rest on the schists without the intervention of breccia of the underlying rocks.

I consider that the Toward sandstones and cornstones were laid down against a more or less straight wall of schists and upon an irregular floor of similar rocks.

They have been faulted slightly along an ancient line of fracture coinciding with the above wall of schist. Along this fracture movement has taken place at several periods in geological time, the most pronounced of these having taken place in pre-O.R.S. epochs.

*Aberfoyle and Balmaha.* In the Aberfoyle and Balmaha district it is known that the Highland Boundary Fault is younger

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than the L.O.R. and older than the U.O.R. Faulted pebbles of quartzite from the conglomerates of the L.O.R. are common. It is in this area that we have the great development of the Boundary Fault series of Cambrian slates, cherts, and grits. There is no Boundary Fault series in Kintyre. Rocks of more or less the same age and nature as the Boundary Fault series are found in Arran but they are not found in situ in Bute. In the Loch Fad conglomerates, however, rocks similar to those found with the radiolarian cherts of the Aberfoyle district are met with and even though cherts are absent it is evident that the series once continued as far S.W. as Bute. This led Clough to the conclusion (Cowal Memoir, p. 89) that

"the exposures from which the fragments of the Loch Fad conglomerates were derived did not make at all so large a show during the Upper Old Red times as they had done previously. This perhaps indicates that the Boundary fault along the Highland frontier represents a line of very old and repeated movement, and this confirms the probability of a large part of the crushing at present seen along it being older than the Upper Old Red Sandstone. In the country between Aberfoyle and Loch Lomond there is a thick crush zone running N.N.E. near the Highland frontier which is certainly of earlier date than the Upper Old Red Sandstone, and very probably there is a still earlier line of discordance of a thrust-like character."

In the schists of Cowal there are numerous faults running in the same direction as the Highland Boundary Fault.

There is no Highland Boundary Fault in Ireland in the position in which it is usually assumed to be, that is on the coast of Cushendall, N.W. of Belfast, and opposite the Mull of Kintyre. The O.R.S. in this part of Ireland rests with striking unconformity upon the schists and many actual junctions between the coarse conglomerates and the schists are found in the Ballyemon Glen S.W. of Cushendall.[1] The principal fault here runs in a N.E. direction along the trend of the Caledonian folding a little W. of Cushendall, but it throws down O.R.S. against igneous rock and N.R.S. This is not the largest fault in the area, however, for the largest occurs at the western margin of sheet 14 and throws Tertiary basalts down against schists.

[1] "Handbook of the Geology of Ireland," Cole and Hallissy, 1924; *Memoir Geol. Surv. Ireland*, Explanation of Sheet 14, 1886.

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As in the case of the Kintyre O.R.S., therefore, these Irish conglomerates were laid down on the south-eastern flanks of the Caledonian highlands. It is stated in the Handbook to the Geology of Ireland (p. 51) that

"lakes probably gathered in the hollows of this early Devonian land, though it is now difficult to trace the boundaries in the Irish area. Broad fans of siliceous detritus accumulated on and spread across the land surface. . . . . The mountain ranges of Dalradian rocks, with their characteristic Caledonian trend, must have supplied an enormous amount of detrital material to the hollow regions of the land. In some parts of the S., muds were accumulated; but on the whole the Devonian deposits indicate beaches and terrestrial taluses of varying coarseness, in which conglomerates predominate, mainly composed of the rocks best calculated to resist prolonged weathering action."

These conclusions have been reached from a study of the Palaeozoic rocks of Kintyre where they are not separated from the Dalradian schists by any line of fracture comparable to the Highland Boundary Fault. The reasons given by me under Toward Point (p. 67) for the formation of the sandstones at that place express my belief as to how these rocks have been laid down all along the north-western margin of the Midland Valley. Facts which further strengthen this view are given in the Conclusion, under Calciferous Sandstone lavas.

From this it will be seen that I admit there exists a fault separating the schists of the Highlands from the sediments of the Midland Valley in other regions of the Firth of Clyde but not in Kintyre. This fault we know in the Loch Lomond region is of M.O.R.S. age but the evidence in the S.W. is that the fault is post-Carboniferous. It is my belief, however, that the magnitude of the fault diminishes as we come S.W. (and as it becomes younger ?) and in many places U.O.R.S. and Calciferous Sandstone lavas end off against schists from which they are not separated by a fault.

The writer hopes to return to the problem of the Highland Boundary Fault. This question requires much more consideration than I have been able to give to it so far.

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5. *Igneous Geology.*

(*a*) *Summary.* KAINOZOIC.

(i) Dykes and sills of crinanite, and one dyke of monchiquite.

(ii) A large rounded boss of fine grained basalt forming the hill of Cnoc nan Gabhar.

CARBONIFEROUS.

*Intrusive.*

(i) Orthophyre and keratophyre furnish the most characteristic rocks of Southern Kintyre. They occur in intrusions perhaps more persistent and larger than anywhere else in the Firth of Clyde. They are found in elongated masses sometimes as much as three or four miles in length and only half a mile in breadth in some parts.

Such masses occur at Largiebann, and to the S.E. of it, with epidiorite, and another stretches from the Mull lighthouse road at Borgadel Water N. to Glenadale Water.

Smaller masses, sometimes as dykes, sometimes as sills and bosses, occur in the neighbourhood of the larger intrusions and occasionally scattered irregularly in other places, as in the area to the E. of Glen Breackerie.

Two isolated intrusions connected with the Killellan " porphyrite " are found cutting the road to the W. of Glecknahavill, and another occurs on the south-western shore of Campbeltown Loch.

Davarr Island is composed almost entirely of orthophyre and similar rocks are found elsewhere cutting the Dalradian schists, O.R.S. sediments, and Carboniferous lavas.

Soda-orthophyre and trachyandesite also occur, and the latter which forms the Killellan Quarry intrusion, is interesting in that it is very rich in the mineral chlorophaeite.

(ii) Dykes: keratophyre as mentioned above and basalt.

(iii) Sills: a group of sills probably of this age occurs among the U.O.R.S. cornstones at the Galdrings, Machrihanish.

(iv) A small volcanic vent filled with agglomerate occurs a little S. of Killypole farm.

*Contemporaneous.*

The Calciferous Sandstone lavas are roughly divisible into a lower and upper division, the lower being essentially basic in composition and consisting of some fine grained jedburgh, but more abundant craiglockhart, basalts. The upper, in addition to very abundant markle and dunsapie basalts, contains a very

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interesting series of albite-olivine-trachytes and trachyandesites, which are admirably exposed in the shore sections at Machrihanish.

The lavas are associated with tuffs and agglomerates and show good columnar structure. Sometimes (in Northern Kintyre) the individual columns are separated from each other by several inches of red iron oxide and calcite.

The soda-trachytes are a group of felspathic lavas in which the felspar is chiefly albite. Orthoclase does occur but is subordinate to the soda-plagioclase. The trachyandesites have phenocrysts of labradorite and sometimes olivine in a groundmass of straightly extinguishing laths of plagioclase.

### Old Red Sandstone.

(i) In the L.O.R.S. occurs an interesting series of volcanic vents, well developed in the Southend district. Two of these occur at sea-level on the shore at Keil Point and the third forms the characteristic rounded hill of Cnoc Garbh. These vents are contemporaneous with the rocks into which they are intruded.

(ii) A great series of conglomerates of igneous rocks occurs both on the mainland and on Sanda.

(iii) Of presumably O.R.S. age are sills of spessartite intruded into the schists on the shore at An Cirein, S. of Earadale Point. This age is given to them on account of their resemblance to similar rocks in the Glen Shira and Glen Orchy region.

(iv) Mapped by Symes within the conglomerates on the shore of the mainland S. of Davarr Island are several bands of felsitic character.

### Dalradian.

The epidorites, since they are included under metamorphic rocks, are not dealt with here.

(*b*) *Kainozoic* The dykes of this age which are so common along the western coast of Scotland are very sparsely found in Southern Kintyre. Those dykes that have been sliced, however, are typical of the Tertiary suite in general and consist of ophitic olivine dolerites and crinanites.

Dyke of olivine dolerite on the shore, past Keil House, Southend. This rock is typical of the olivine dolerites and consists of bright brown augite, clear fresh olivine, and abundant plagioclase laths in ophitic relation with the augite. Green and yellowish decomposition products occur in parts of the slide.

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The rock is closely related to the crinanites, and contains several large spherulitic aggregates which are characteristic of the analcite-olivine-dolerites.

A similar, much fresher, and more ophitic olivine dolerite cuts a "porphyrite" intrusion S. of Ballygroggan, Losset. This dyke is represented alone on the one-inch map.

An olivine dolerite dyke cuts the most northerly of the three new sills described from An Cirein, S. of Earadale Point. This dyke is not shown on the one-inch map. It is intruded into limestone, quartz schist, and green schist but is not continued in a direct line through them. Instead, when it meets the green schists after passing through the limestone and siliceous bands, it turns sharply westward for a distance equal to its own breadth and then continues vertically upwards. A small stringer leaves the eastern corner of the lower part of the dyke, runs up into the green schist and soon dies out.

A large olivine dolerite dyke with fine grained margins occurs at the most northerly cave on the shore S. of New Orleans (Ballymenach, S. of Kildalloig Bay).

A dyke on the road to the Mull Lighthouse between the main mass of porphyrite and the stringer to the W. contains abundant brown secondary interstitial material.

The first (i.e. most northerly) dyke in the Galdrings section, S. of Machrihanish, is a Kainozoic dolerite of this group. Hitherto it has been looked upon as of Carboniferous age but it is much fresher than the lavas around it. Although on the whole the ferro-magnesian minerals have been replaced by yellow and brown decomposition products yet a fair amount of olivine is still in a fresh condition.

The intrusion in the burn, S. of Killypole farm, where it flows N. before turning E. to flow into Killypole Loch, has fine grained margins and coarse centre and is closely associated with a small volcanic neck of Carboniferous age which is filled with agglomerate.

The central part of the rock is a typical ophitic dolerite composed of large laths of plagioclase and plates of augite, with abundant decomposition products after olivine. Apatite needles and large cubes of magnetite are abundant.

Considering the size of the area dealt with crinanites are not abundantly represented. The best occurrence is the dyke which is intruded into the sandstones of the L.O.R.S. at the eastern end of Carskey Bay on the S. coast. Even in this rock analcite is not

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abundant but it does occur in the interspaces between the plagioclase laths. Spherulitic aggregates of a colourless zeolite are common and help to connect this rock with that one which occurs a little to the E. of it among the coarse conglomerates, and which was briefly described under olivine dolerite. The olivine in the present rock is quite fresh and the augite is of the purple variety. Decomposition products of green and brown serpentinous material are also plentiful.

Only one dyke of monchiquite has been found, but it is of especial interest, chiefly because it is now described for the first time and is unrepresented on the Survey's one-inch map. This could be accounted for by the fact that the rock is intruded into lavas of Carboniferous age and can hardly be distinguished from them. Yet it stands up through the lavas as dykes often do.

It occurs between Uisaed and Eudan nan Gallan, Machrihanish. It follows a winding course, stands up through the shingle on the beach and runs a considerable distance out to sea. It inclines steeply to the S.W. and sends stringers into the lavas, while it has also picked up pieces of basalt and schist. In it are two bands with coarse weathering, extremely rich in large anorthoclase and augite crystals, and containing patches of a red radial zeolite. The dyke has a width of 41 inches; the western band of zeolites occurs 9 inches from the margin and the other 14 inches from the opposite (eastern) edge.

It is characteristic of Kintyre dykes in general and of crinanites in particular that they are banded, as this one is, with zeolites and the bands usually correspond with a definite set of joints parallel to the margins. In quarry sections of dykes these joints are noticeable. Geikie[1] has described and figured a similar arrangement of amygdules in dykes from other parts. He states that "the amygdules of a dyke offer certain peculiarities which serve in a general way to mark them off from those of an outflowing lava. They are smaller, and more uniform in size, than in the latter rock. They are also more regularly spherical and less frequently elongated in the direction of flow. Moreover, they are not usually distributed through the whole breadth of a dyke, but tend to arrange themselves in lines especially towards its centre."

Although unmapped on the present map of the district this

[1] "History of Volcanic Action during the Tertiary period in British Isles," p. 38.

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dyke seems to have been noticed by Nicol[1] for he states that " further north (i.e. than the Galdrings) similar veins (i.e. dykes) traverse the massive or bedded trap and often project from its surface like crude walls."

Since this rock is only seen to cut through the Carboniferous lavas it is difficult to assign a definite age to it. It may be of Permo-Carboniferous age or it may represent an unusual (in this district) phase of Tertiary igneous activity. The difficulty of age determination is all the greater since similar rocks of both these ages occur in Scotland. Monchiquites of Permo-Carboniferous age with large anorthoclase phenocrysts occur in the Elie district of Fifeshire, where they have been described by Geikie[2] and monchiquite dykes of Tertiary age occur in the peninsula of Ardmucknish, Argyllshire, and have been described by Flett from the Orkneys.[3] Eyles[4] has recorded similar rocks from Ayrshire.

Perhaps the nearest approach to the present rock is the monchiquite and ouachitite of Colonsay. The former of these is a typical monchiquite but the latter contains no olivine. Unlike the Kintyre rock, however, the coloured mineral other than augite is biotite.

Flett, who also described the Ardmucknish occurrences, states that monchiquite dykes with large anorthoclases are known to him only from one locality, E. Fife, where they occur in some number around Elie. The anorthoclases in this Kintyre monchiquite often measure 3 ins. in length and give typical diamond shaped sections.

The mass of the rock is dark, fine grained and basaltic. Typical sections show numerous phenocrysts of augite in a clear isotropic groundmass. The augite occurs in crystals of two sizes—larger phenocrysts and minute prisms. It has a faint colour and is often zoned and shows multiple twinning. It may be replaced by pseudomorphs of fibrous chlorite with margins of black iron oxide. Many of the augites show good hour-glass structure between crossed nicols and though on the whole they have a clear greyish colour traces of purple are seen at the edges. In some parts of the section small prisms of brown pleochroic hornblende

[1] *Op. cit.*, p. 416.

[2] " Geology of East Fife," *Mem. Geol. Surv. Scotland*, 1902, p. 240.

[3] *Trans. Roy. Soc. Edin.*, xxxix, p. 387.

[4] *Geol. Mag.*, lxi, pp. 471-2.

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are abundant. Calcite and serpentinous material and chlorite occur as secondary products, and surrounding one patch of carbonate is a border of silica. Sometimes there are spherulitic aggregates of silica. The calcite is often associated with the augite, the central parts of which may be entirely replaced by it. Numerous grains of magnetite and needles of apatite also occur in the groundmass, which most likely consists of analcite. It is both isotropic and has a very low D.R. with possible traces of cleavage. A marginal variety shows much scarcer but larger phenocrysts of augite in a dark fibrous and turbid groundmass richer in iron oxide than the above and doubtless containing glass. No olivine has been met with in this rock and since a typical monchiquite has crystals of both augite and olivine the Machrihanish dyke may be described as a hornblende fourchite.

A large dolerite sill occurs W. of Tirfergus Hill running N.W. along the slopes of the higher ground on the north-eastern side of the valley of Loch Oridale In hand specimen this rock is a brownish fairly coarse dolerite with occasional large clear felspar laths. Under the microscope it is seen to be made up of an ophitic plexus of felspar laths and augite, with considerable amounts of yellowish brown decomposition products. The olivine is entirely replaced by this serpentinous material. The augite is sometimes of a pale purple colour and is quite fresh. Labradorite is the most abundant felspar, but alkali felspar is also common and forms outer zones on the lime-soda varieties and it also occurs alone. Clear patches of interstitial quartz are found in the slide; magnetite occurs in fairly large pieces and apatite needles are plentiful.

There is an intrusion of crinanite on the roadside between Homeston and Glecknahavill (5 miles from Campbeltown along the Campbeltown-Glen Breackerie road). In the field I found it difficult to decide whether the intrusion was in the form of a dyke or a sill, but it seems probable that the latter best explains its mode of occurrence. It is a coarse gabbro-like rock resembling the Clauchlands sill in Arran.

The rock is made up of large plates of augite, with laths of labradorite and abundant analcite. The augite is for the most part the ordinary pale green variety but patches are of a brownish colour and pleochroic. There are also large areas composed of clear and brownish radial zeolites which in many cases replace felspar. Magnetite is very abundant.

A more or less circular intrusion of Dalmeny basalt, half a mile

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in diameter, forms the conspicuous hill of Cnoc nan Gabhar on the northern side of the Campbeltown-Southend road, and mid-way between Campbeltown and Southend.

The rock in hand specimen is a fine grained non-porphyritic basalt, and there seem to be no variations from this normal rock. In thin section it is seen to be made up of microphenocrysts of olivine, and occasional laths of plagioclase, in a dense felspathic groundmass containing abundant minute prisms of augite and grains of magnetite. In the groundmass there is abundant pseudo-isotropic material (R.I. greater than C.B.) which may be alkali felspar with very low double refraction.

Since this rock is intruded into the schists there is no evidence as to the exact age of the intrusion, but from the nature of the rock it seems most likely that it belongs to the Kainozoic intrusive suite.

The chemical analysis of this rock is given in Table 6.

Other small basalt intrusions possibly of the same nature are indicated on the one-inch map.

(*c*) *Carboniferous.* (1) *Sub-Acid and Associated Intrusive Rocks.* A short digression on the terms "keratophyre" and "bostonite," as used here, is necessary at this point.

The name "bostonite" was originally applied by Hunter and Rosenbusch to dyke-rocks practically similar in composition, both chemical and mineral, to trachyte except that dark ferro-magnesian silicates are absent and soda felspars are exceptionally abundant. The term was based on the description of porphyries from near Boston (Mass.), and was given in the attempt to carry out the separation of the dyke-rocks, as a "distinct grand division," from the plutonic and volcanic rocks.

Kemp and Marsters[1] described the group thus: "Under the microscope the rocks are at once seen to have a marked and characteristic trachytic structure, i.e., the groundmass consists of small felspar laths, not infrequently in fluidal arrangement. Between the rods one can sometimes detect small masses of interstitial quartz. The groundmass is invariably holocrystalline and the felspars are idiomorphic. . . . . Although generally kaolinised, it can be generally seen that they are but once twinned, and, as shown by analysis, they appear to be both orthoclase and anorthoclase."

[1] *Bull. U.S. Geol. Surv.*, No. 107, 1893.

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Later, Kemp, in "A Hand Book of Rocks" (1911) following the attempt of Hunter and Rosenbusch to separate volcanic from other rocks, states that the bostonites are much the same as dyke-keratophyres.

Harker[1] defines bostonite as consisting essentially of felspar, quartz being never abundant and the ferro-magnesian silicates typically absent. Phenocrysts are scarce or wanting, the bulk of the rock being a groundmass of little felspar rods often with partial flow-disposition and recalling the structure of the trachytes. In many examples a high percentage of soda with little or no plagioclase evident, points to a soda-orthoclase or anorthoclase and indicates an affinity with the keratophyres.

Iddings,[2] however, says the term was originally applied to syenitic aplites and felsites, for the most part non-porphyritic felsite with no mafic minerals. The rock at Marblehead neck, Mass., to which the name was first applied, is aphanitic and slightly porphyritic and forms a small massive outcrop, visible only at low tide, whose exact mode of occurrence is not known. From its association, Washington regards it as being an effusive rock and for this reason, though the name bostonite was first applied to it as the type rock, he says it is really a keratophyre.

Again, Washington,[3] returning to the original usage of the terms states that the main difference between bostonite and keratophyre is that the latter name is applicable only to flows while bostonites are intrusive.

Holmes[4] defines a bostonite as a leucocratic-alkali-syenite-aplite with trachytic texture, formed almost wholly of alkali felspar, and makes no reference to the mode of occurrence, and in opposition to the attempt made by the other authors to separate the intrusive rocks from the effusive we find Smellie[5] remarking that whereas in the Cumbraes and other parts of the Clyde area trachytes and bostonites occur as minor intrusives, in Bute the bostonites are found only among the lavas.

The most general paper dealing with this ambiguous nomenclature is Tyrrell's " The Trachytic and Allied Rocks of the Clyde

[1] " Petrology for Students," 1923, p. 119.
[2] " Igneous Rocks," 1913.
[3] *Journ. Geol.*, vii, pp. 284-294.
[4] " The Nomenclature of Petrology," 1920, p. 49.
[5] *Trans. Geol. Soc., Glasgow.*, xv, iii, 1914-15.

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Carboniferous Plateaus."[1] In it he divides these rocks into three groups,

Those characterised by soda-felspar, i.e. those with predominance of felspar near to albite.

Those with approximately equal proportions of potash and soda felspars and,

Predominantly quartz-bearing types.

He uses the terms bostonite, trachyte, and keratophyre for rocks with essentially the same chemical and mineralogical composition, differing only in texture. Thus the bostonites are defined as of comparatively coarse but equidimensional texture, the constituent felspars defining a more or less fluxional arrangement. The trachytes are much finer grained and the minute laths are similarly arranged with a flow disposition, whereas in keratophyre the groundmass is dense and felsitic.

Leitch and Scott,[2] however, disagree with Tyrrell's definitions and say that the term keratophyre should be reserved for those aphanitic sub-acid rocks with a dominant soda-bearing felspar, such as orthoclase or albite; bostonite for similar rocks in which the amounts of soda and potash felspar are more nearly equal and trachyte for the dominantly potassic type. According to this definition albite-bostonites would become keratophyres.

So far little has been said about keratophyre itself because keratophyres have been described in a paper by A. K. Wells entitled "The Nomenclature of the Spilitic Suite. Part I: The Keratophyric Rocks,"[3] A repetition of some points and conclusions, however, is necessary.

As far as can be made out from the above discussion the main difference between bostonite and keratophyre seems to be one of texture. Some writers restrict the name bostonite to intrusive rocks only, others call flows with the typical structure and composition of bostonites also by the same name and such a nomenclature is not without precedent. Markle basalts, for example, are found intrusive as well as effusive. Wells suggests distinguishing between the lavas and intrusions by using the qualifying names "intrusive" and "extrusive" and believes that the presence or absence of flow structure is of no petrological significance and therefore of no classificatory value. From his paper we

[1] *Proc. R.S.E.*, xxxvi, iii, No. 18, 1915-16.
[2] *Trans. Geol. Soc. Glasgow.*, xvi, ii, 1916-17
[3] *Geol. Mag.*, lix, No. 698, Aug., 1922.

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learn that the felspar characteristic of bostonites is soda-orthoclase. In lime-bostonites (maenaites), the soda-orthoclase is replaced by oligoclase. Wells states tht the essential difference between keratophyre and bostonite lies not so much in mineral composition and texture, as in descent.

That is " keratophyre " should be related to the intermediate members of the spilitic suite both intrusive and extrusive and to the spilitic suite only.

This suite of rocks he divides into three:—

The basic members, the spilites.

The intermediate members, the keratophyres and,

Acid members or quartz-keratophyres.

This, however, is a mistaken belief. Keratophyres are no doubt often associated with spilites, as at Tayvallich and other places, but they also occur in districts where they have no connection with these rocks, as in the case of the typical Craigmushet keratophyre of Gourock. Keratophyres and bostonites have been shown to occur together and form modifications of one intrusion and in connection with ordinary basalts.

In the present paper I intend to restrict the terms " bostonite " and " keratophyre " to rocks differing only in texture with practically the same chemical and mineralogical composition. The bostonites are characterised by their " comparatively coarse but equidimensional texture the constituent felspars defining a more or less fluxional arrangement," the keratophyres by their dense and felsitic groundmass. In this sense few bostonites have been found in Southern Kintyre.

Closely connected with the above group is the rock called orthophyre and varieties of this are described here with the keratophyres. According to Holmes[1] the epithet orthophyric is given to the hypidiomorphic texture on a small scale sometimes developed in the groundmass of porphyries, the controlling mineral being felspar in stout prisms. Orthophyres themselves are porphyries in which the phenocrysts are orthoclase or soda-orthoclase and in which quartz is inconspicuous.[2] Some rocks which have been called orthophyres contain notable amounts of quartz in the groundmass. Somewhat similar rocks have also been called quartz-monzonite-porphyry. The latter is character-

[1] " Pet. Methods and Calculations," 1920, p. 342.
[2] Iddings, " Igneous Rocks," II, 1913, p. 182.

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ised by the association of orthoclase and a soda-lime-felspar as chief constituent minerals.

Tyrrell[1] has described orthophyres from the Cumbraes and from Holy Island, Arran.[2]

The essential difference between orthophyre and the keratophyre group is that the former is an orthoclase rock and the latter is a group of rocks characterised by soda-felspar. The orthophyres in the present paper are not so very different from the bostonites in composition but their textures are so characteristically orthophyric that the term bostonite cannot be applied to them.

Orthophyres and keratophyres are the most characteristic rocks of the southern end of Kintyre. They occur as intrusions perhaps larger and more persistent than anywhere else in the Firth of Clyde. They are of Lower Carboniferous age and may be found intruded into everything up to and including the lavas of the Calciferous Sandstone. The most important intrusions of these rocks which are described in detail in the following pages are:—Davarr Island; The three intrusions to the east of Killellan; The elongated intrusion running N. and S. from Glenadale Water to Borgadel Water and cut through by the road to the Mull lighthouse; Kilkerran Quarry, Campbeltown. Similar rocks are well developed among the metamorphic rocks around Largiebann and between Knockstaple and Strone.

*Davarr Island.* This island, rising to a height of 378 ft., stands at the entrance to Campbeltown Loch and about two miles due E. of the town of Campbeltown. It consists almost entirely of a plug of orthophyre. To the W. and N.W. are deposits of both the 25-foot and 50-foot raised beaches. At low water mark on the southern and south-eastern coast is a platform of the igneous rock. The latter is intruded into O.R.S. and metamorphic rocks. Quartzite conglomerate occurs on the slope N.W. of the ruins on the south-western part of the island. Basal breccias of the O.R. resting directly upon mica schists (with much biotite) and quartz schists are found N.W. of the Well at the pier opposite Macringan's Point. The metamorphic rocks show good thrusting from the N.W. The igneous rock is well jointed and many large caves have been worn out along these lines of weakness or along small faults, several of which are found radiating in from the coast.

[1] *Pr. Roy. Soc. Edin.*, 1917, xxxvi, p. 293.

[2] *Geol. Mag.*, 1913, pp. 305-306.

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The characteristic rock of Davarr Island is of a full brown colour with fairly abundant rectangular phenocrysts but about half a dozen varieties with different colours and aspects in hand specimen may be found anywhere at the foot of the cliffs. A common variety to the S. along the sea caves, is essentially of a green colour with large crystals of a brighter green. Approaching this rock in appearance are others of a dark greenish brown with large rectangular crystals of felspar usually lighter in colour than the groundmass. Somewhat similar to the normal brown rock are more decomposed reddish brown specimens in which the phenocrysts are seen to be beautifully zoned and quite clear and glassy with others in which the larger crystals are of a darker and more massive brown than the groundmass.

Microscopically the typical rock may be described as a soda-orthophyre with abundant quartz. Sometimes the finer grained and very iron-stained varieties can only be called quartz-keratophyres. In the slides of the reddish brown variety phenocrysts and groundmass alike are masked by the abundance of disseminated haematite. Usually the haematite is arranged zonally in the felspars and a dark band always runs round the crystal at a short distance from the margin, which is often quite clear and fresh. In other cases it is arranged along the cleavages. Sometimes the part of a felspar crystal within the haematite band is quite clear and composed of minute spherulitic aggregates of secondary silica.

Large phenocrysts are very abundant and are composed for the most part of orthoclase (soda variety). Phenocrysts of albite are also common but the amount of iron oxide makes accurate determination of the felspar impossible. Some of the larger felspars have given way entirely and have been replaced by silica, iron oxide, and other indeterminable material.

The groundmass is typically orthophyric and often the elongation of the felspar laths causes it to approach the bostonitic. Orthoclase is the most abundant constituent of the groundmass but some of the laths are of plagioclase and show multiple twinning. The groundmass is also rich in primary quartz, which occurs in large optically continuous plates enclosing laths of orthoclase. These enclosed orthoclases and those forming the immediate boundary of the quartz are freer from iron oxide staining than the others. Magnetite and apatite also occur (the magnetite in fairly large euhedral crystals) and the haematite sometimes becomes as dark in colour as the magnetite



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In one section of a very reddish brown rock the groundmass is quite opaque except for occasional small laths of felspar. In the same slide and separated from the above by a band of somewhat fragmental material with quartz and felspar fragments the rock is richer in tiny felspar laths (with straight extinction) which have a partial flow arrangement, but they are embedded in a dense keratophyric groundmass. Quartz is very abundant and the orthoclase phenocrysts are very large.

A pale brown variety which admits of better microscopic study has phenocrysts of orthoclase and albite and much secondary calcite. The albite phenocrysts are abundant and show good twinning. These larger crystals are embedded in an orthophyric groundmass with only a very occasional lath showing multiple twinning and subordinate amounts of quartz. In others there are exceptionally large phenocrysts of albite broken up into rectangular fragments by the working of chlorite along the cleavages and which causes these phenocrysts to resemble the groundmass. Occasionally the plagioclase phenocrysts become more basic than in these rocks hitherto described and though still possessing good albite twinning they have R.I. greater than C.B. Most of these phenocrysts are albite-oligoclase. Some are andesine and are zoned with chlorite and sometimes completely replaced by it. Chlorite and other decomposition products and magnetite are abundant and within some of the plagioclase phenocrysts are agate structures with central parts of quartz followed outward by a band of iron-oxide and finally consisting of large areas of chlorite made up of minute spherulites. Apatite inclusions in the felspar are vey common.

It is a characteristic feature of these rocks that the greater the amount of albite-oligoclase and andesine the greater is the amount of secondary chlorite, and, when the felspar is chiefly orthoclase and albite, decomposition has resulted in the formation of abundant red iron oxide. It is impossible to say if the chlorite of these rocks has resulted from the decomposition of some original ferromagnesian mineral in the rocks.

The specimen of Davarr Island orthophyre of which the analysis is given later contains many beautiful fresh phenocrysts of albite-oligoclase in a felspathic groundmass with a little quartz and fragments of a brown pleochroic mineral.

*Kilkerran Quarry.* This is a large quarry on the main road on

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the southern shore of Campbeltown Loch and a short distance due E. of the town.

The intrusion is composed of very homogeneous rock and always shows the same brown or flesh colour. It is markedly porphyritic but the phenocrysts are of exactly the same colour as the groundmass. This rock is intruded into the Beinn Ghuilean schists and forms a characteristic hill with a steep southern face where the valley forming the continuation of the Crosshill reservoir depression has been worn out along an E.—W. fault.

Under the microscope this rock is seen to be an orthophyre consisting of phenocrysts of soda orthoclase, in glomeroporphyritic aggregates, in a felspathic groundmass. The latter is composed mainly of orthoclase but some of the laths show multiple twinning. In the groundmass the felspar laths have a tendency to be arranged with partial flow structure. Both primary and secondary quartz is abundant.

*Killellan House Intrusion* On the roadside near the " 5 mile-to-Campbeltown " stone on the Campbeltown-Southend road a large quarry has been opened in the most southerly of the three " porphyrite " intrusions. The characteristic rock has a reddish brown felsitic appearance and is non-porphyritic but for occasional yellow and green decomposition spots. In some specimens may be found phenocrysts of very decomposed felspar.

The microscopic study of the rock shows it to be different from the rocks above described as orthophyres; it is a true *quartz-keratophyre.*

There is abundant haematite, and as a rule the phenocrysts are converted into calcite. In one slide free from the prevailing iron staining the phenocrysts are large and fairly abundant. Some are entirely decomposed and represented by aggregates of calcite and silica, while others are quite fresh and composed of sanidine and albite. Often the central parts of the latter are altered. There are numerous pseudomorphs in chlorite after some ferromagnesian mineral. Although the groundmass is fine-grained it contains a considerable amount of quartz which has developed in a sort of pseudo-graphic intergrowth with the felspar.

*Intrusion between Killellan House and Quarry.* The rock here is a reddish brown fine grained and rather decomposed mass with occasional clear porphyritic laths of felspar. Under the microscope it is seen to be a quartz-keratophyre with phenocrysts of orthoclase and albite (decomposed).

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*Killellan Quarry*. This is the name of the quarry in the most northerly of the three intrusions at Killellan. The Quarry is half in the O.R.S. cornstone and half in the igneous rock. The junction between the two rocks is perfectly sharp and the cornstones dip away from the junction at a high angle.

The main rock in the quarry is dark and basaltic with a splintery fracture. The characteristic feature of the rock is the presence of abundant chlorophaeite which occurs in small rounded patches and in thin parallel stringers. In the larger patches the chlorophaeite shows good conchoidal fracture and everywhere shows the diagnostic change of colour from olivine-yellow to quite dark and black. Phenocrysts of felspar also occur. Besides the basaltic rock there are brown slaggy and vesicular varieties with numerous cavities, some of which are open, but others contain rounded patches of yellowish and pale green decomposition products. Some of the rocks show a purplish colour with indefinite felspar phenocrysts. This rock is a typical *trachyandesite* consisting of plagioclase (labradorite chiefly, andesine frequently) and augite phenocrysts in a groundmass of orthoclase laths with semi-trachytic structure. Magnetite is not abundant but occurs in large sporadic grains. Patches of brown and brownish green chlorophaeite are very abundant.

Other varieties of more keratophyric character in hand specimen are comparable to the above but are much finer grained and trachytic and have much disseminated iron oxide which prevents their details from being made out. One slide is very rich in quartz in the groundmass and on account of its association with the typical trachyandesite it may be called a quartz-trachyandesite. Otherwise in its obscurity it is similar to the quartz-keratophyres. In these varieties there is no chlorophaeite.

In a short paper[1] on " Chlorophaeite in the dolerites (tholeiites) of Dalmahoy and Kaimes Hill, Edinburgh " Dr. Campbell and J. W. Lunn mention (p. 440) that they observed chlorophaeite in a slide from the Heddle collection of thin slices in the University College, Dundee. This slide is labelled Killellan and the authors have called the rock a trachybasalt and stated that it is presumably from the Carboniferous lava belt of Southern Kintyre. There can be little doubt that Heddle's slide represents what I have here described as the *intrusion* of *trachyandesite* at Killellan and Dr. Campbell's and Mr Lunn's presumption is incorrect.

[1] *Min. Mag.*, xx, No. 110, 1925, pp. 435-440.

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The prevailing colour of the chlorophaeite in the present rocks is brown and yellowish brown and it almost invariably has an agate structure made up of darker and lighter bands. It is occasionally closely associated with augite but the latter is so fresh that the chlorophaeite cannot have been derived from it. Closely connected with the readjustment of the constituents of the chlorophaeite into the banded form is the formation of many radial growths of silica and chlorite. The chlorophaeite is often cracked and broken up into more or less rounded pieces. Then alteration commences along these cracks and a thin rim of silica needles is formed. The central masses of these pieces are still in the form of greenish brown chlorite and after this complete readjustment takes place and the chlorophaeite is entirely replaced by spherulitic aggregates.

*Strone Intrusion.* This is an elongated intrusion in the metamorphic rocks of the Mull and running in an N.—S. direction from the southern slopes of Glenadale Water, across the Strone Water, to Borgadel Water. A little to the N. of the latter burn and between it and the road to the Mull lighthouse it bends to the W. at right angles and continues in this direction for three quarters of a mile. The specimens of the rock which were sliced were obtained from two quarry sections where the government road cuts across the intrusion.

In hand specimen the colour of this rock varies from a bright brown through a yellowish brown to a dark grey and some specimens show a greenish tint. It is fine grained and porphyritic with large phenocrysts of clear glassy or flesh coloured felspar. Usually the majority of these felspars are decomposed.

Microscopically the normal brown rock is a soda-orthophyre with large phenocrysts of orthoclase and albite. Many of the albites which are bordered with chlorite appear as if they might be of secondary origin but there are others which are undoubtedly primary and as a rule these are bordered with brown clayey decomposition products. The phenocrysts are often arranged in glomeroporphyritic aggregates and for the most part they are rounded by absorption. The groundmass is composed of rectangular sections of orthoclase and interstitial quartz. Secondary chlorite is very abundant and usually the arrangement of these minerals, the orthoclase embedded in quartz and surrounded with chlorite, has the effect of simulating granophyric texture. Sometimes quartz fills triangular spaces between the felspar phenocrysts.

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Besides being found in zonal bands concentric with the margin of the plagioclase phenocrysts and in the above manner in the groundmass, chlorite occurs too, in patches made up of small agate aggregates.

In some slides the groundmass is exceptionally rich in disseminated haematite which makes its study almost impossible, but from clearer patches in some it seems as though they were more trachytic than the normal rock above described and if so they must approach the bostonites. In these, however, it is unusual to have phenocrysts and the present rocks are very porphyritic. Others, again, have the dense, compact, and iron-stained groundmass which is typical of the keratophyres and the resemblance to the quartz varieties of these is still further increased by the occurrence of quartz in clear rounded grains.

Although in the above descriptions no mention has been made of any phenocrysts save orthoclase and albite there are others such as andesine and hornblende which vary from very scarce to abundant.

In a slide of the grey coloured variety which is similar to the normal rock in having a coarse orthophyric groundmass there are numerous phenocrysts of andesine besides the usual orthoclase and albite. Accompanying this increase in basic felspar are a few scattered and decomposed crystals of brown hornblende. Likewise in the groundmass there is an increase in the amount of mechanically zoned felspar which probably indicates plagioclase and one slide contains an irregular patch of cognate rock which is decidedly basaltic in appearance, and which is composed of plagioclase laths and magnetite with much green decomposition material.

In all these rocks apatite is a constant accessory and magnetite occurs in many of them.

*An Cirein.* An interesting intrusion, the nature of which is not obvious, has been found on the beach at An Cirein, S. of Earadale Point on the W. coast. The rock in hand specimen is a pale flesh-coloured and greenish compact felsite with abundant black shiny plates of biotite. Under the microscope the groundmass is seen to be composed of dense felspathic material and plentiful quartz, and carries phenocrysts of felspar and biotite. The latter is a bright brown colour and strongly pleochroic and the felspar is usually represented by calcite pseudomorphs. Some, however,

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show the remains of multiple twinning and the rock is registered, therefore, as a quartz-biotite-keratophyre.

*Mid Losset Intrusion.* This occurs a quarter of a mile W. of S. of Mid Losset, and is well exposed in a large quarry section where the rock is comparatively fresh and dark in colour. A great many of the phenocrysts, however, are decomposed but others are quite clear and glassy

Microscopically the rock is different from those already described because the groundmass shows good fluxion structure due to the parallel orientation of the felspar laths. These are composed of both orthoclase and plagioclase (with multiple twinning and straight extinction). The phenocrysts are of orthoclase and albite and the rock is very closely related to the bostonites. Quartz and secondary calcite are also fairly abundant.

*Miscellaneous Intrusions.* All the smaller intrusions of this group of rocks are very decomposed and iron stained, and from a microscopical examination all that can be said is that they are either keratophyres or quartz-keratophyres.

(2) *Dykes.*

Three new dykes of Jedburgh basalt have been found cutting the red sandstones in the Chiscan Water, E. of Gullan Deon fort. (Chiscan Water enters Killeonan Water a little W. of Kilchrist Castle, 3 miles S. of Campbeltown). Another intrusion cuts a band of cornstone on the eastern slope of the hill W. of a tributary of the Chiscan Water, and on the southern side of the main water.

Several small dykes of a similar nature outcrop among the coarse conglomerates on the southern shore of Kildalloig Bay.

These rocks are all very decomposed jedburgh basalts. Coloured minerals are entirely replaced by green, yellow, and brown chloritic and serpentinous products. The coarsest variety is from the dyke on the S. side of Kildalloig Bay, and it is made up of fairly large laths of plagioclase often replaced by calcite, green and yellowish green decomposition products, and abundant magnetite.

The felspar in the third dyke to the S.E. in Kildalloig Bay is replaced by pale green chlorite, and brown iron oxide is disseminated through the whole slide.

The dykes in the Chiscan Water are much finer grained and, though decomposed, are more typical of this group of Carboniferous intrusions. The most easterly of the three mentioned above is almost completely bauxitised. In these rocks there are

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large rounded cavities filled with calcite and pale green spherulitic aggregates or with both.

Markle basalts occur in dykes somewhat similar to the jedburgh varieties, but often fresher, and may be indicated on the one-inch map as porphyrite.

The large 25 ft. markle basalt dyke cutting the O.R.S. cornstones in the Galdrings, Machrihanish, is shown in fig. 18, and is of particular interest. Concerning the two dykes in this cliff section Nicol wrote, " A little further to the south (i.e. than the northern end of the Galdrings section) the manner in which the trap has found its way to the surface is very beautifully shown. The shore, where laid bare by the waves, between high and low water mark, consists of beds of highly contorted mica-slate dipping about 35° to S., 45° E. Higher up, on the elevated sea beach, the rocks are concealed by blown sand and the debris from the steep and lofty cliff above. This cliff is formed of sandstones and limestones which project in thick beds from the turf. In the place represented by the accompanying diagram figure"—(Fig. 2 of Nicol, fig. 18 of author)—"two veins of trap run nearly vertically up the cliff; and are again seen in horizontal section on the shore intersecting the mica slate. The smaller vein, on the north, is about 4 feet wide, and is of a dark greenstone, divided into horizontal columns in the centre, but with verticle laminae on the side. . . . . The larger vein is about 40 feet wide and is of a grey porphyritic basalt amygdaloid. . . . . The smaller vein appears to spread out in a tabular mass above while the larger vein terminates abruptly in a rounded knoll."

This description of the section is more or less correct. It is true that it is difficult to trace the small dyke through the lavas but from the microscopic examination of the rock I consider that it is a Kainozoic dolerite, and not a Carboniferous intrusion. It is more difficult to make sure of the manner in which the larger dyke terminates upwards, chiefly because where it comes to the surface the lavas have been denuded away for a few yards, and it is a fact that it widens slightly when it comes to the top of the cornstones. To say, however, that it furnished some of the lavas, is, I consider, beyond the evidence available.

An intrusion has also been recorded in Tirfergus Burn due S. of Low Tirfergus and another on the cart road S. of Killypole and W. of the intrusion shown on the map as occurring in the

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burn, while another occurs in Glenahinty Burn, W. of Achnaslishaig Hill.

In the large Galdrings dyke rounded patches of chlorophaeite, with borders of pyrites, can be recognised in hand specimen.

The rock of the Tirfergus Burn intrusion is made up of large plates of labradorite bordered with zones of magnetite and haematite and occasional large crystals of augite, often decomposed, in an equidimensional felspathic groundmass with much iron oxide. Apatite also occurs.

In the Galdrings dyke phenocrysts of plagioclase and augite (subordinate but in large plates) are embedded in a groundmass of plagioclase, minute prisms of augite, and magnetite grains. A slide from the top northern side of the dyke shows plagioclase phenocrysts in a groundmass of smaller laths, with much calcite and chloritic material. In the Glenahinty dyke skeletal magnetite is especially well developed, and there are abundant needles of ilmenite.

Flow structure is fairly well developed in the rock from the S. of Killypole.

At least one intrusion of dunsapie basalt has been sliced from the burn (a tributary of the Breacherie Water) which flows southward to the W. of Achnaslishaig Hill. The dyke is intruded into grits and gneisses and has large euhedral augite crystals projecting from a weathered surface. There are also many xenoliths of grits.

Under the microscope this rock is seen to be composed of abundant phenocrysts of plagioclase, augite, and olivine in a groundmass of plagioclase laths, augite, and magnetite. The olivine is decomposed and represented by pseudomorphs in brown spherulitic aggregates, colourless silica, and calcite. Magnetite occurs in skeletal aggregates, and there are numerous needles of ilmenite. In the marginal variety of the rock the minerals are all entirely replaced by chlorite and calcite.

Many intrusions of "porphyrite" are described under the sub-acid rocks and the exact nature of many of the intrusions is not known.

(3) *Sills.* Sills of jedburgh basalt which have not been recorded previously are intruded into cornstones of U.O.R.S. age at the Galdrings, S. of Machrihanish and are shown in fig. 18.

The northern and smallest of these is the most accessible and is seen to cut sharply across the bedding of the cornstones and

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die out upwards to the S. before reaching the first dyke. The other two sills which occur to the S. of the large dyke die out downwards to the N.

All three, as seen under the microscope, are very decomposed, and all the coloured minerals have been entirely replaced. Disseminated brown iron oxide, magnetite grains, and needles of ilmenite are abundant. In the top southern sill even the plagioclase laths have been bauxitised. That they are jedburgh basalts of Carboniferous age seems evident from the slide of the lowest southern intrusion which is the freshest. One section of this rock, however, approaches mugearite in composition and texture, although fairly coarse. It is also very decomposed and contains many aggregates of green and brown spherulites. The felspar laths are chiefly oligoclase and are arranged with a rude parallel alignment.

Another very decomposed igneous rock has been found in a small exposure of cornstones in a field N. of Ballygroggan and W. of Mid Losset. This consists of small stringers 6 inches across, the nature of which, both on account of the decomposed state of the rock and smallness of the exposure, it is impossible to say.

(4) *Basalts and other Contemporaneous Igneous Rocks.* On looking at the map of Southern Kintyre one is naturally struck by the apparent simplicity of the Calciferous Sandstone lavas, for everywhere they are subdivided into two persistent horizons— the lower being mapped as basalt and the upper as porphyrite.

The name porphyrite has been much used in this area for rocks of very different character, and intrusive porphyrites have been shown to be sub-acid rocks of the keratophyre-bostonite group. From my study of Kintyre porphyrites it seems to me that the older geologists used the term " porphyrite " for rocks which in the field were characterised by porphyritic texture the dominant phenocrysts being felspars and the rocks usually having a reddish brown colour due to decomposition. The keratophyres and orthophyres are all brown or reddish brown, and in the present section we deal with porphyritic lavas of Calciferous Sandstone age which are often decomposed and richly charged with haematite.

Tyrrell[1] states that the rocks which the older geologists designated " porphyrite " in the Carboniferous of the W. of Scotland, belonged to the group of Markle basalts, and according to Harker[2]

[1] *Trans. Geol. Soc. Glasgow*, XIV, pt. II, 1911-12, p. 229.
[2] " Petrology for Students," 1923, p. 176.

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" those petrologists who restrict the name andesite to rocks of late geological age, apply to their pre-Tertiary equivalents the name 'porphyrite.' Under the same title they include various rocks of hypabyssal types, and it is to these latter that we have already confined the name. Again, certain English petrologists have used the name 'porphyrite' for andesites which have undergone some degree of change by weathering, etc., a distinction which seems scarcely important enough to be recognised in classification or nomenclature." In the report[1] on British Petrographic Nomenclature by the Joint Committee appointed by the Geological Society of London and the Mineralogical Society, a porphyrite is defined as a porphyritic rock with crystalline (including cryptocrystalline) groundmass containing soda-lime felspar.

Since, in Southern Kintyre, the Calciferous Sandstone lavas are found in two areas separated from each other by about 4 miles of O.R.S. and Dalradian rocks, it will be convenient to study these areas separately.

The larger of these occurrences is that which stretches from Losset (S.W. of Machrihanish) to Killellan (midway between Campbeltown and Southend). In talking of this it will be referred to as the Machrihanish lavas. The Southend lavas occur on the south-eastern coast and form a semi-circular outcrop inland from Macharioch Bay to the headland half a mile E. of Rudha McShannuich.

*Markle Basalts.* Markle basalts are by far the most abundant type of contemporaneous igneous rock in Southern Kintyre. Most of the slices described here represent rocks taken from the shore section in the Machrihanish lavas from the W. of Uisaed to the Carboniferous sediments near the Machrihanish Water. One or two show occasional phenocrysts of olivine or augite and have been included in the present section because the microscopic examination shows how great an excess there is of felspar over the other minerals.

Tuffs and agglomerates are common associates of the lavas of the shore section mentioned above and on the eastern side of Uisaid there are abundant patches of radial silica in the lavas. Agglomerates are abundant on the shore N. of the houses at the Saltpans and stretch from there to the E. of the point known as the Big Scone and Little Scone.

[1] *Min. Mag.*, 1921, xix, No. 92, pp. 137-147.

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In describing the basalts of the other types it will be unnecessary to give field relations other than the localities from which they have been obtained.

For a summary description of the group it is found most convenient to subdivide it into a series of minor groups which pass into one another by insensible gradations. In thin sections they form a remarkably uniform series. These subdivisions are,

*a.* Those with entirely felspathic groundmass and no augite. There are occasional phenocrysts of olivine represented by pseudomorphs in iddingsite.

Some slides show good flow structure in the groundmass and abundant iron oxide; others have no flow structure and the ground mass is very fine grained; others again have no flow structure but have a groundmass composed of fairly large somewhat stumpy rectangles of plagioclase. Numerous irregular patches and small grains of both haematite and magnetite occur.

*b.* In this there are abundant minute granules of augite in the groundmass. In the rock from the quarry S.E. of the cliffs at the Galdrings there are a few decomposition products which might represent original olivine but they are too indefinite to say so. The rock is in a line with the large Galdrings dyke to be described later and the slice was made to see whether or not it actually was a continuation of the dyke. Microscopical comparison suggests that they are different. A subordinate type has an extremely fine grained groundmass with micro-phenocrysts of plagioclase smaller than the main phenocrysts embedded in it. One slide has fairly large fresh phenocrysts of olivine.

*c.* No augite occurs in this subdivision but magnetite grains are found in the groundmass. In a slide of the lava from the W. of Saltpans there is an extraordinary amount of iron oxide in the groundmass. Some slides have abundant secondary chlorite in aggregates with agate structure. There is a little secondary silica within some of the patches of green. Some of the bands in the agate masses are quite isotropic while usually the central parts are aggregates of little spherulites. The felspar phenocrysts are all somewhat altered and charged with iron oxide, and the olivine is represented by pseudomorphs in iddingsite.

*d.* A slide of the rock from near the top of the lavas at Machrihanish has abundant secondary calcite which from its association with fragments of plagioclase is undoubtedly secondary after that

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mineral. With the calcite is a considerable amount of silica. Iron oxide is abundant.

*e.* Rocks from the eastern side of Uisaed are found to be closely allied to dunsapie basalts and on the border line between them and markles. From the predominance of felspar I prefer to register them with the latter.

Microphenocrysts of olivine and augite with plagioclase are embedded in a groundmass of felspar with fair amounts of iron oxide. The olivine occasionally occurs in euhedral crystals replaced by brown and green decomposition products. There is a very little granular augite in the groundmass.

*f.* Large phenocrysts of olivine and plagioclase in a groundmass of felspar, augite, and magnetite. These are basalts that agree more with the type markle variety than any of the others.

In all the markle basalts from Uisaed the olivine is represented by pseudomorphs in iddingsite. The augite granules in the groundmass are minute and sometimes very scarce. Haematite and magnetite are abundant. In one part of the rock, where there is an accidental xenolith of quartzite, made up of irregular grains of quartz, there is a concentration of pyroxene around it. The amount of pyroxene here is remarkable considering the scarcity in the rock as a whole and the grains furthest from the quartzite border are sometimes of considerable size. (Fig. 20). Further, immediately outside the band of pyroxene there is a band composed entirely of plagioclase with no iron oxide or coloured mineral. Hawkes[1] has described corroded quartz crystals with reaction borders consisting of minute prisms and grains of monoclinic pyroxene from Icelandic pitchstones and in some of his sections rounded aggregates of granular pyroxene occur in such a manner as to suggest complete resorption of the original quartz xenocryst. Allan[2] has figured in Kinghorn basalts quartz fragments which are surrounded by glass carrying augite microlites, and an outer zone of granular and prismatic augite.

Some of these basalts show very good flow structure and some are exceptionally rich in iron oxide in the groundmass.

Besides the phenocrysts of olivine and plagioclase, augite sometimes occurs in large slightly altered and broken crystals.

*g.* In another variety from Uisaed there are large patches of analcite. In one of these rounded masses there are two small

[1] *Q.J.G.S.*, lxxxi, pt. 2, p. 332.
[2] *Trans. Roy. Soc. Edin.*, liii, pt. 3, p. 500.

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fragments of a brown mineral with good cleavage and a set of partings at right angles to the cleavage. The mineral is strongly pleochroic from a yellow through a reddish brown to a purplish brown. At the borders of, and sometimes within the cavities which have been filled with analcite are little prisms of green augite.

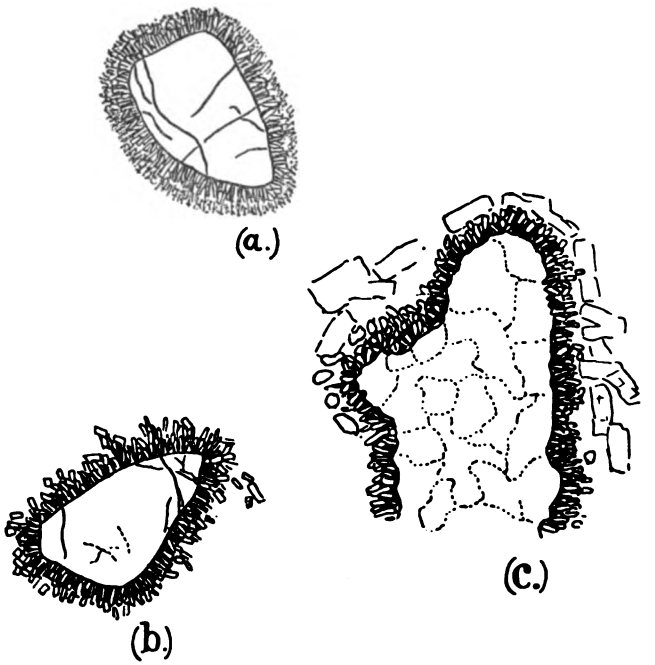


Fig. 20.

(*a*) Quartz pebble in lowest Carboniferous lava over cornstones, Galdrings, Machrihanish.

(*b*) Quartz pebble in lavas, Rudah McShannuich, Southend. Both pebbles show resorption of borders and well defined cracks. Surrounding the pebbles is a concentration of green and colourless pyroxene prisms and granules.

(*c*) Quartzite pebble in markle basalt, Uisaed, showing concentration of pyroxene around the edge, followed outward by a pyroxene-free band of felspar.

*h*. A very lightly coloured markle basalt has been obtained from near the head of Tirfergus Burn where it is faulted against the tuffs. The groundmass is very felspathic with less iron oxide than most of those previously described. Olivine phenocrysts

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are represented by one large pseudomorph of reddish brown pleochroic iddingsite, and smaller spherulitic aggregates of pale green chlorite, some of which are scattered through the groundmass as smaller microphenocrysts. Most of the plagioclase phenocrysts are albitised and some are full of the scaly mica described by Bailey and Grabham in "The Albitisation of Basic Plagioclase Felspar."[1]

*i.* At the Slip Rock or Carrick Caban, below the railway station, Machrihanish, is a remarkable rock which seems to bridge the gap between the markle basalts proper and the series of trachytes and trachyandesites with which it is associated and which will be described later. It is a markle-mugearite. It contains abundant large phenocrysts of plagioclase and olivine. The plagioclases are of labradorite and at times even more basic and show splendid examples of albitisation. The olivines are represented by fibrous green chlorite and black or very dark brown iron oxide. The groundmass, however, is not that of a markle basalt but of a mugearite. It consists of laths of oligoclase and a little magnetite and shows good fluxion arrangement of the minerals.

Typical basalts of the markle type are found in the Southend lavas to the W. of Cove Point. Ferromagnesian minerals are absent from them but there is much magnetite and haematite.

A slice of essentially felspathic basalt from Cnoc Araich, Aucharua, contains, besides abundant large phenocrysts of felspar with good mechanical zoning, numerous pseudomorphs in iron oxide and greyish brown opaque material after olivine and smaller crystals and granular aggregates of augite. Haematite is exceptionally abundant in this slide.

*Jedburgh Basalts.* The lowest lava, that immediately over the cornstones in the Galdrings cliff section, Machrihanish (fig. 21), is a basalt of this type made up of abundant microphenocrysts of olivine replaced by a green platy mineral with strong pleochroism and high double refraction (chlorite?). The groundmass contains somewhat similar green material but here it occurs in irregular blobs with agate structure and is isotropic, resembling the chlorite described in some of the markle basalts. Veins of calcite are common in the slice and there is one corroded pebble of quartz with a corona of pyroxene which is green near the quartz but greyish away from it.

[1] *Geol. Mag.*, [v], vi, pp. 250-256.

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The rock from the corresponding horizon in Tomaig Glen, and more than 5 miles removed from the Galdrings, has numerous pseudomorphs after olivine and microphenocrysts of reddish brown augite in a groundmass of felspar laths and minute granules of augite. The felspars in the groundmass have parallel orientation.

From the Uisaed—Machrihanish section the jedburgh basalts are very decomposed and the secondary products in chlorite, silica, serpentine, and carbonates are abundant. The augite is for the most part of a bright brown colour and is often laden with magnetite grains and is apparently altering to some sericitic material.

A rock similar to these has been found between Skerry Fell and Killypole and this contains both brown and colourless augite and abundant spherulitic aggregates of decomposition products.

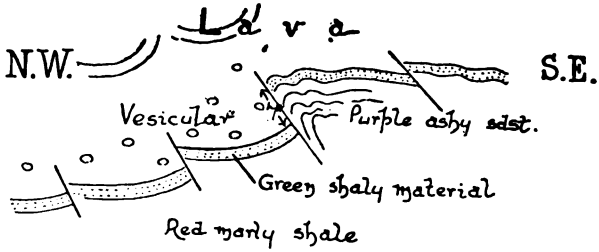


**Fig. 21.—Junction between lavas and cornstone in the Galdrings cliff section, showing small overthrusts indicating movement of overlying lavas from S.E. to N.W.**

In the contemporaneous jedburgh basalt into which the Killellan keratophyres and trachyandesite are intruded, the olivine is represented by reddish brown iddingsite.

The rocks of the Southend lavas which are described here as jedburgh basalts form a remarkable series of ophitic dolerites widely developed to the E. and N.E. of Kilbride, Southend. In hand-specimen they vary from fine grained basalts to coarse, decomposed pegmatites. The coarser varieties contain abundant zeolites and are often crossed by veins of chalcedonic and amethystic quartz.

The lowest rock which has been sliced was obtained from a short distance to the E. of Rudha McShannuich and it is an ophitic basalt consisting of fresh laths of plagioclase and plates of augite, and abundant secondary chlorite and iron oxide. Im-

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mediately above this the rock is much finer grained and the augite occurs only in small granules and the plagioclase in minute laths.

Slides of the coarser rock forming the high ground E. of the Stone Circle and Cist near Kilbride have been cut. Under the microscope these consist of large plates of plagioclase and pale green augite with much interstitial silica and sericitic material. In some cases the rocks tend to porphyritic texture and the large plagioclases are embedded in a felt of short stumpy laths of felspar without twinning. Magnetite, haematite, and apatite also occur. Occasionally when the ophitic texture becomes unusually well developed the augite and plagioclase appear in graphic intergrowth with each other. In one slide there is a dark brown band of tuff composed of broken fragments of plagioclase and augite cemented together with haematite. Ilmenite often occurs in large plates and radial patches of bright green chlorite are common.

A vitrophyric variety of coarsely ophitic basalt occurs among the above rocks E. of the Stone Circle. Plagioclase laths are here embedded in a greyish opaque material with abundant needles of ilmenite. In some, interstitial calcite reaches important amounts and embedded in it are laths of perfectly fresh plagioclase.

S.E. of the Tank and N.E. of Cuildrain, Macharioch, is a beautiful ophitic basalt somewhat similar to those already described but with more abundant secondary chlorite. It differs, however, from the others in containing large six-sided crystals of turbid material with numerous veins of black iron oxide ramifying through it. These crystals of turbid material seem to be pseudomorphs after olivine.

*Craiglockhart Basalts.* Rocks of this type from Machrihanish and Uisaed contain extremely large plates of augite and pseudomorphs after olivine. The latter are represented by yellow, green (varying to almost colourless) and bright reddish brown secondary products. These pseudomorphs are roughly concentrically banded, the outer band being bright green, the next reddish brown and the central band is a pale yellowish green in colour. The augite phenocrysts are usually bordered with a granular zone of their own material or a zone rich in iron oxide grains. They are often traversed by veins of yellow serpentine. The groundmass shows good flow structure, the clear fresh laths of plagioclase being surrounded with small grains of augite and magnetite. Secondary chlorite is abundant in the groundmass of some of the rocks.

A variety from the north of Eudan nan Gallan approaches the



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dunsapie type in that the groundmass in which the large phenocrysts of olivine (pseudomorphs) and augite are embedded consists of plagioclase laths in a still finer ground composed for the most part of minute magnetite and augite grains.

Craiglockhart basalts from the Southend lavas have been obtained from the E. of Cove Point, Macharioch, and from Cnoc Airidhe, Aucharua.

The rock from the former locality consists of large pseudomorphs in iron oxide and serpentine after olivine and glomeroporphyritic aggregates of augite in a groundmass of plagioclase laths, augite, and magnetite. Chlorite decomposition products are common in the groundmass.

The Cnoc Airidhe rock differs from the above in being finer grained and in possessing more abundant, though smaller, phenocrysts. The olivine instead of being, as in the last case, represented chiefly by iron oxide is free from ore and entirely in the form of yellow and yellowish brown serpentine. The large augites are also collected in glomeroporphyritic aggregates and serpentine decomposition products are scattered abundantly through the groundmass.

*Dunsapie Basalts.* The best basalts of this type have been obtained from the south of Mid Losset ( a very short distance south of " 568," half a mile south of the above, 6 inch sheet cclvi, N.E. and S.E. Argyll). They consist of large plates of labradorite, augite, and olivine in a groundmass of plagioclase, augite, and magnetite. The plagioclase phenocrysts are well zoned and show distinct albite twinning. The large augites are of a brown colour, zoned, and show steel grey double refraction. The pyroxene in the groundmass is colourless. Some calcite occurs within a few of the augite phenocrysts. The olivine is represented by serpentinous and chloritic pseudomorphs of green, yellow, and yellowish brown. Fresh olivine occurs in some of the pseudomorphs. The magnetite sometimes occurs in very large plates.

A less typical, but very abundant rock has been obtained from near the boat-house on the southern side of Killypole Loch.

*Dalmeny basalts.* A red platy rock belonging to this group of basalts has been collected fron the W. of Cove Point, Macharioch, Southend.

Under the microscope the characteristic feature of the rock is the abundance of bright reddish brown pseudomorphs after olivine in microphenocrysts The pseudomorphs are of iddings-

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tite, often with light coloured margins and darker centres. The groundmass is composed of plagioclase laths, granular augite, and magnetite grains. The plagioclases define a good flow structure. Some of the pseudomorphs are so rectangular and elongated that it is doubtful if they can be pseudomorphs after olivine.

A very fresh fine-grained basalt was sliced from the quarry rock on the northern side of the road at Kilbride. Under the microscope it shows abundant microphenocrysts of olivine and augite, the latter less abundant than the olivine but still plentiful. The groundmass is essentially felspathic but contains a little augite (in ophitic relations with the plagioclase) and some turbid brown opaque decomposition product. But for the absence of glass or analcite in the groundmass, unless the brown material be secondary after such, the rock resembles the hillhouse type of basalt. It is, however, better called a jedburgh-dalmeny.

*Albite-Trachytes.* The rocks which are included in this group are essentially felspathic lavas with good flow structure but the felspar is chiefly albite. Orthoclase does occur but is subordinate in amount to the soda-plagioclase. In trachyandesites the groundmass has good trachytic structure and consists of both acid plagioclase and orthoclase. The felspar phenocrysts, however, are usually of labradorite. In some, such as that from the Meikle Bin,[1] the groundmass is thoroughly orthophyric and in it augite, magnetite, and plagioclase felspar play a very subordinate role. The phenocrysts in the Meikle Bin rock are labradorite, augite, and olivine. In the rocks now being considered pseudomorphs after olivine are abundant as phenocrysts.

Just as the Meikle Bin trachyandesite bridges the gap between the trachybasalts and the trachytes, this albite-trachyte series bridges the gap between the trachyandesites themselves and the trachytes proper.

These rocks occur on the shore at Machrihanish immediately opposite the church and at Knocantymore and E. and S.E. of it. On the 6 inch map sheet cclvii, S.W. Argyll, the Machrihanish exposure is at the " T's " of H. and L.W.M.O.S.T., i.e., on the south-eastern side of the slip at Carrick Caban and to the S. of the latter.

On the shore they resemble fine grained and well bedded tuffs which have been folded and contorted, but on a closer examination

[1] "The Geology of the Glasgow District," *Mem. Geol. Surv.*, 1925, p. 184.

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it is seen that they are really lavas with good flow structure and splitting easily along the cleavage thus produced.

In hand specimen they are greyish brown or reddish brown rocks with abundant flesh coloured felspar phenocrysts, all of which have parallel orientation. Some varieties are vesicular, the vesicles being filled with yellow and yellowish green products of decomposition.

Under the microscope these rocks are seen to be albite- and soda-orthoclase-trachytes with or without olivine.

The phenocrysts of felspar occur for the most part as very long rectangular plates, though the orthoclase is short and stumpy. The length of the plates is always parallel to the flow structure in the groundmass. The orthoclase sometimes shows carlsbad twinning and often the mottled extinction characteristic of the soda variety. The plagioclase phenocrysts consist of both albite and oligoclase but the former is by far the most abundant. As in a rock from the N.W. of Knocantymore some of the felspars are altered to calcite. Apatite is very abundant in most of the rocks. It occurs in fairly large basal or prismatic sections.

The olivine phenocrysts are always decomposed and represented by serpentinous pseudomorphs with black borders and cracks of iron oxide. In some slides there are large albites collected together in glomeroporphyritic aggregates.

The groundmass is very fine grained and trachytic with much disseminated iron oxide. Orthoclase seems to be the most abundant and constant constituent but in some the nature of the laths and the apparent presence of twinning suggests a considerable amount of oligoclase.

The iron oxide in the groundmass is often scattered equally through the rock, or collected into abundant more or less rounded aggregates, or arranged in bands parallel to the flow structure.

Harker in his " Petrology for Students " (1923, p. 167), mentions this rock and states, " Good examples of olivine-trachyte are found in the Carboniferous about Campbeltown, Kintyre. These are of more sodic composition, and they contain phenocrysts of albite and oligoclase as well as orthoclase. The olivine is represented by serpentinous pseudomorphs with a deep border of iron oxide and there is little indication of any other ferro-magnesian mineral."

From Smellie's description[1] of the more acid lavas from the

[1] *Trans. Geol. Soc. Glasgow*, xv, iii, 1914-15, p. 358.

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southern end of Bute it is difficult to understand the true nature of the rocks. They are labelled trachytes or bostonites, and in hand specimen seem to be identical with the Kintyre trachytes. The irregular staining with haematite mentioned above is also characteristic of certain of the Bute lavas.

*Orthophyric Trachyte.* Skerry Fell and Skerry Fell Fad (781 ft.), the two conspicuous peaks S. of Machrihanish and E. of N. of Killypole house are composed of very light coloured lava which in hand specimen differs little from a compact white sandstone.

Under the microscope the rock is seen to be remarkably fresh. It is composed of scarce phenocrysts of orthoclase in a felted groundmass of the same mineral with considerable quartz. The orthoclase often has the mottled extinction characteristic of the soda variety. Apatite is abundant in small needles and there is a fair amount of iron oxide in well defined grains and in one or two large patches.

The remarkable feature of this rock is the abundance of orthoclase or soda-orthoclase to the exclusion of the true soda felspar, albite. The groundmass has not the extremely fine grained or cryptocrystalline nature which is characteristic of felsites as a rule, but is of the nature of the groundmass in most of the orthophyres which are described under the intrusive rocks of Calciferous Sandstone age.

*Trachyandesites.* A rock resembling the above more than the ordinary basalt in hand specimen has been obtained from a little to the W. of Saltpans, Machrihanish. It is light grey in colour and evidently much decomposed and contains fairly numerous small phenocrysts of plagioclase. Under the microscope it is seen to be altered into an opaque turbid material which makes the examination of the slice difficult. There are abundant phenocrysts of labradorite, often zoned chemically and mechanically and altering in some parts into a colourless mineral with high double refraction and possibly a mica. Some plates of strongly pleochroic iddingsite doubtless represent phenocrysts of olivine. The groundmass is trachytic but the exact nature of the felspar is indeterminable.

Another trachyandesite is associated with the albite-trachytes at Carrick Caban, Machrihanish. This rock is composed of phenocrysts of albitised labradorite and pseudomorphs after olivine in serpentine, iddingsite, and iron oxide, in a groundmass of small straightly extinguishing laths of felspar. These small laths

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are arranged with parallel orientation and one or two show multiple twinning and are of oligoclase. Orthoclase is also present in the groundmass. Little cubes of magnetite are fairly abundant and the rock is assuming a basaltic character. Secondary chlorite and silica are plentiful.

(*d*). *Old Red Sandstone.* (1) *Pebbles from the Conglomerates and Vents.* A collection of the igneous rocks filling the vents of the Lower O.R. and from the great thickness of conglomerates of the same period was made at the following localities;

(i) From the small vents at Keil Point, and from the sediments and agglomerates between Keil and Dunaverty, Southend.

(ii) From the conglomerates on Sanda, and from the small vent on the north-western shore of the island.

(iii) From the shore section S.E. from Kildalloig Bay.

Some of the boulders from the vents in (i) are rounded while some are angular and it is evident as stated by Sir A. Geikie that the rounded boulders did not assume this character in the deposits where they are now found but that they were waterworn before the existence of the O.R.S. vents. Hence, these vents breaking through the sediments incorporated rounded pebbles and boulders of igneous rocks in close contact with perfectly angular pieces of more or less similar material.

The large size together with the rounded nature of the boulders, is also taken by Geikie to indicate the great amount of wave action which must have taken place during L.O.R.S. times. Besides the igneous rocks described below, quartzite boulders and masses of agglomerate also occur and the structures and relations of the rocks in the field have already been mentioned.

The chief igneous rocks are:—andesites, rhyolites, and trachytes.

The andesites are further subdivided into hornblende-andesite, biotite-andesite, and pyroxene-andesite.

In hand specimen they are all more or less similar being usually dark mauvish rocks with phenocrysts of light coloured felspar. but many are extremely decomposed.

The hornblende-andesites are the most important, and under the microscope they are seen to be composed of abundant phenocrysts of plagioclase and pseudomorphs after hornblende in a brown devitrified groundmass. The hornblende is represented by aggregates of black iron oxide and these are often in the form of good basal sections. In one slide of a pebble from the shore west of Sanda pier brown relics remain in the central parts of some

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of the pseudomorphs and indicate that when the rock was fresh the hornblende of these andesites was of a brown colour. Chlorite and silica are also common replacement minerals, and they are often surrounded with a band of dark brown iron oxide which in turn passes outward into the black oxide.

The felspars, which range up to labradorite, are much altered but retain their rectangular form. They contain many inclusions of the groundmass and calcite is abundant as a secondary product.

The groundmass is very turbid and represents a devitrified glass. It contains a few microlites of felspar with repeated twinning, while in one slide the whole is made up practically of infiltrated silica.

The phenocrysts of altered hornblende are not equally abundant in all the slides but vary from slices in which any part of the field is crowded with good basal sections to others in which the mineral is almost absent.

In the most typical of the biotite-andesites the hand specimen somewhat resembles those described above but for the presence of abundant crystals of black shiny mica. The felspar phenocrysts have been replaced by a white clayey material which is isotropic and has a R.I. $>$ C.B. Some of the aggregates are microgranular. The large biotite crystals are remarkably fresh and they are banded with bright brown and lighter and even greenish tints. The groundmass of the rocks is microgranular.

The other rocks of the group differ from the hornblende-andesites only in the presence of biotite instead of hornblende, and a devitrified glassy groundmass is in one case heavily charged with silica infiltrations.

Only one specimen of pyroxene-andesite has been obtained from the sediments at Keil, Southend. In hand specimen the rock is very decomposed but under the microscope its character is quite definite. It shows abundant pseudomorphs after hornblende and pyroxene with turbid and altered felspars in a fine textured groundmass. The hornblende has been replaced by black and brown iron oxide while the pyroxene has been replaced chiefly by chlorite. The felspars are much altered, and spherulitic aggregates of silica associated with calcite are abundant.

The rhyolites fall into two groups, (i) those with flow structure and no marked banding, and (ii) those with marked banding of the glassy groundmass.

(i) In hand specimen the rocks of this class vary from brown compact felsitic rocks (sometimes with occasional specks of green

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decomposition matter, but often very hard and turning the edge of a pocket knife) to dark basaltic types.

Under the microscope they show a groundmass of devitrified glass stained irregularly with dark brown iron oxide and carrying much magnetite. In one slide the groundmass is of extremely dark glass, and in another with a light groundmass there is a faint hint of banding.

Embedded in this glassy base are two generations of phenocrysts, the tiny laths of both orthoclase and plagioclase indicating the flow structure and the larger rectangular or resorbed phenocrysts of plagioclase and subordinate orthoclase. In most cases the felspars are very much altered and the final product of alteration is a pseudomorph in chlorite and calcite. Chlorite also occurs irregularly in the groundmass of these rocks. The presence of this mineral is remarkable because coloured minerals are absent from all the rocks, but in one variety from Elephant Rock, Sanda, there are small phenocrysts of comparatively fresh biotite.

(ii) The rhyolites with marked banding are represented by specimens from Dunaverty and Keil, Southend.

In the hand these are remarkably characteristic and might be called quartz-porphyry. Of a brick brown colour they are dotted all over with clear glassy crystals of quartz. In one there are also irregular and angular fragments of felspathic material.

As seen under the microscope numerous bands of dark and light brown twist and curve around quartz and plagioclase grains. Quartz phenocrysts are the most abundant. They are perfectly clear and transparent and vary in shape from resorbed hexagonal crystals to perfectly rounded grains. Sometimes they are quite angular. The plagioclases show inclusions of glass along the cleavages and occur in numerous small angular and rectangular fragments.

In another slide what appears to be clear patches of quartz are seen under crossed nicols to be fragments of quartzite made up of quartz grains with subordinate plagioclase. Individual grains of quartz also exist and calcite is a common secondary product.

Still another variety shows broken-up bands of brown spherulitic glass with large felspar laths and basal and vertical sections of fresh brown biotite. Infiltrated silica occurs in the groundmass.

The trachytes resemble the brown felsitic rhyolites in hand specimen but as seen under the microscope they differ from them in having the groundmass composed entirely of tiny laths of straight-

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extinguishing felspar. Pale brown iron oxide is disseminated through the rocks and minute grains of magnetite are also common. The felspar laths are all aligned in one direction.

Phenocrysts are not abundant and those that are found are composed of plagioclase and hornblende. The latter is represented by pseudomorphs in magnetite grains and chlorite, while the chlorite has often found its way into the plagioclase and completely replaced it with the liberation of much calcite. Secondary quartz also occurs.

The trachytes described here have been found in the small neck on the north-western shore of the island of Sanda.

This examination of igneous boulders is all the more interesting and necessary on account of the fact that lava flows of Old Red Sandstone age are not found in this area and the nearest locality where they remain is in the neighbouring island of Arran. Here they occur in the north-eastern part and are associated with conglomerates of igneous rocks. Lavas also occur in the upper division of the O.R.S. in Arran.

The following is the description of the volcanic series in the Memoir on the Geology of North Arran (p. 171).

> " In this series the rocks occurring in the field as lava-flows are of a decidedly basic facies, and appear to be more closely allied to the basalts than to the typical andesites. It is probable, however, that typical andesites occur. On the other hand, an examination of some of the fragments from the conglomerate, which is found overlying these lavas, shows that they belong to the more acid class of andesites, and may be referred in part to the hornblende-andesites. It thus appears that a more acid series of andesites were undergoing denudation at the time of the formation of the conglomerate, while the earlier outpourings partook of a more basic character. A similar range in the composition of the lava-flows is exemplified in many other Lower Old Red volcanic areas and the sequence from basic to more acid is common and characteristic."

A description is also given (p. 172) of hornblende-andesites which agree in detail with rocks described in this paper but basic lavas represented by basalts and olivine basalts are also described from the same lavas.

Slide 9391, in the Survey collection, of a pebble in the Lower Old Red conglomerate from Scar, E. of Creag Mor, Auchencar, shows microscopically " numerous idiomorphic crystals and

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crystal-groups of brownish hornblende, for the most part now almost entirely replaced by pseudomorphs of iron oxide. Sometimes the inner portion of the crystal retains some of the original brown colour, but there is invariably a deep opaque border of iron-oxide. . . . . The felspar phenocrysts are fairly numerous. They are evidently mainly plagioclase, probably an acid variety, though some individuals show the Carlsbad twinning. Apatite is accessory, and of a brownish tint. The matrix consists mainly of small felspar microlites (trachytic type), though a good deal obscured by small flecks of iron-ore."

Further reference will be made to these pebbles in the summary.

(2) *Sills.* Three sills of spessartite are intruded into the metamorphic rocks on An Cirein, two thirds of a mile S. of Earadale Point, on the western coast of the area, and one mile N.W. of Cnoc Moy. Like the last series of sills these are also unrecorded on the published one-inch map. The most northerly of the sills is cut across by a basalt dyke.

They are very decomposed, and calcite, chlorite, and silica, as secondary products, make up the greater parts of the sections. Occasionally fresh plagioclases remain, and many stringers of chlorite and magnetite grains represent original biotite in the most southerly sill. Brown biotite and prisms of hornblende (brown) occur in the other rocks. Skeletal ilmenite and abundant needles of apatite also occur.

The nearest approach to these rocks are typical spessartites described in the memoir on the " Geology of Oban and Dalmally." These contain more abundant idiomorphic brown hornblendes and with an increase in the amount of biotite some of the rocks may be classed with the kersantites. Sills and dykes of spessartite with interstitial orthoclase and quartz are common in Glen Shira and Glen Orchy, and a dyke of kersantite cuts the O.R.S. lavas at the head of Loch Scamadale, Lorne. Hornblende and augite lamprophyres of O.R.S. age occur as sills south of Stronchullin in S. Knapdale.

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## (*e*) ANALYSES OF KINTYRE ROCKS.

TABLE I.

| | 1. | A. | B. | 2. | 3. | 4. | C. | D. | E. |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 64.23 | 64.54 | 60.41 | 59.45 | 58.50 | 60.00 | 60.60 | 58.30 | 56.20 |
| $TiO_2$ | tr. | 1.09 | 1.74 | tr. | tr. | .35 | .92 | 1.40 | 1.00 |
| $Al_2O_3$ | 16.28 | 15.83 | 16.06 | 17.02 | 18.42 | 17.05 | 17.55 | 18.13 | 17.40 |
| $Fe_2O_3$ | 1.97 | 1.75 | 3.14 | 1.24 | 4.70 | 2.97 | 1.17 | 3.59 | 3.70 |
| FeO | 3.15 | 2.80 | 3.32 | 3.66 | 1.76 | 2.27 | 6.08 | .90 | 3.40 |
| MnO | .22 | .26 | .28 | .55 | .23 | .16 | .35 | .23 | .20 |
| MgO | 1.74 | 1.01 | 1.26 | 1.72 | 2.59 | 1.26 | 2.04 | 2.36 | 2.50 |
| CaO | 2.25 | 2.13 | 2.07 | 2.85 | 3.05 | 3.58 | 4.02 | 3.11 | 5.20 |
| $Na_2O$ | 4.33 | 5.25 | 4.87 | 4.72 | 4.34 | 4.35 | 3.97 | 5.83 | 5.00 |
| $K_2O$ | 3.82 | 2.95 | 3.28 | 4.37 | 3.69 | 4.17 | 2.73 | 3.72 | 3.60 |
| $H_2O+$ | 1.10 | 1.39 | 2.20 | .70 | .90 | 2.65 | tr. | .90 | } 1.3 |
| $H_2O-$ | .70 | .42 | 1.66 | 3.50 | 1.60 | 1.00 | .20 | 1.23 | |
| $P_2O_5$ | .09 | tr. | .23 | .07 | .16 | .20 | .32 | .40 | .50 |
| $CO_2$ | — | .27 | .15 | — | — | — | — | .06 | — |
| S | — | — | — | — | — | — | — | — | — |
| $Cr_2O_3$ | — | .01 | — | — | — | — | — | — | — |
| $FeS_2$ | — | .15 | — | — | — | — | — | — | — |
| $Li_2O$ | — | tr. | — | — | — | — | — | — | — |
| C | — | tr. | — | — | — | — | — | — | — |
| | 99.88 | 99.85 | 100.67 | 99.85 | 99.94 | 100.01 | 99.95 | 100.6 | 100.00 |

1. Orthophyre, Mull Lighthouse Road, 5 miles W. of Southend, Kintyre, Anal: W. H. and F. Herdsman.

A. Plagiophyre, Sill in L.O.R. conglomerate, Pap Craig, 2½ miles S.W. of Symington. *Summ. Progr. Geol. Surv.* for 1925 (1926), p. 128.

B. Quartz-keratophyre, Craigmushet, Gourock. P. A. Leitch and A. Scott, *Trans. Geol. Soc. Glasgow*, XVI, II, 1917, p. 286.

2. Orthophyre, Kilkerran Quarry, Campbeltown, Kintyre, Anal: W. H. and F. Herdsman.

3. Orthophyre, Davarr Island, Campbeltown, Kintyre, Anal: W. H. and F. Herdsman.

4. Trachyandesite, Killellan Quarry, 4 miles S.W. of Campbeltown, Kintyre, Anal: W. H. and F. Herdsman.

C. Trachyandesite, Snaefellsjökull, Iceland. G. W. Tyrrell, *Trans. Roy. Soc. Edin.*, LIV, iii, p. 749.

D. Trachyandesite, 3 miles S.W. of Eaglesham. *Summ. Progr. Geol. Surv.* for 1923 (1924), p. 135.

E. Average Trachyandesite, G. W. Tyrrell, "Principles of Petrology," 1926, p. 126.

In Table 1, the analysis given in columns 1, 2 and 3 accord fairly well with the average keratophyre as calculated by Daly (Igneous Rocks and Their Origin, 1914, p. 22). They are a little less alkalic and the last two are poorer, while the first is richer, in

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$SiO_2$ than the calculated keratophyre. Accompanying the slight decrease of the alkalies there is a correspondingly slight increase in the percentage amount of CaO. The variations in the compositions of these Kintyre rocks are reflected in the variations of the rocks of each intrusion in hand specimen and under the microscope. The amounts of MgO are fairly high considering that it is contained in secondary chlorite. That some of the varieties of these rocks might be called plagiophyres is evident from a comparison of the plagiophyre in column A with the previous ones, especially with the rock from the Mull lighthouse road which has variations described as trachyandesite. The close resemblance between the Gourock quartz-keratophyre and the Kilkerran and Davarr rocks is also seen from a comparison of columns B, 2 and 3, and the resemblance is one which applies also to their field relations and more or less general aspect in hand specimen.

As can be seen from columns 4 and C, the Killellan Quarry trachyandesite is remarkably well matched by the trachyandesite from Snaefellsjokull, Iceland. The relations of this rock have already been discussed by Dr. Tyrrell, who points out the close correspondence between Lacroix' doreite from the Auvergne and the Iceland trachyandesite. In Jan Mayen the trachyandesites are intermediate between the alkali- trachytes and the trachybasalts. The Eaglesham trachyandesite (col. D), is also comparable with these rocks, and a bostonitic trachyte from Lugton [*Summ. Progr. Geol. Surv.* for 1923 (1924), p. 135], makes a slight connecting link between the soda-orthophyres and the trachyandesites, and, as will be seen from other parts of this paper, the Kintyre trachyandesites are closely connected in the field with the orthophyres, some of which have undoubted bostonitic resemblances. In the orthophyre from the Mull lighthouse road, too, I have described varieties under the microscope which are trachyandesites. The $SiO_2$, $Al_2O_3$, and alkalies in the trachyandesites from the Meikle Bin, Campsie Fells (Glasgow Memoir, 1925, p. 183) are practically similar to those in the Kintyre rock as shown in column 4. There is more MgO and slightly more CaO in the latter, while the iron is a little under that in the Meikle Bin analysis.

Compared with the average trachyandesite as calculated by Dr. Tyrrell in his " Principles of Petrology " (Table 1, column E.), the Kintyre, Iceland, and Eaglesham rocks, represented by columns 4, C, and D, are all quartz-trachyandesites.

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TABLE II.

| | 5. | F. | G. | 6. | H. |
|---|---|---|---|---|---|
| $SiO_2$ | 40.25 | 39.54 | 43.55 | 44.24 | 46.45 |
| $TiO_2$ | 2.70 | 2.72 | 2.52 | 2.70 | 3.11 |
| $Al_2O_3$ | 13.07 | 13.74 | 14.60 | 16.73 | 16.98 |
| $Fe_2O_3$ | 5.81 | 4.05 | 5.34 | 2.06 | 3.94 |
| FeO | 7.24 | 7.85 | 7.46 | 9.42 | 8.57 |
| MnO | .32 | .40 | .55 | .32 | .48 |
| MgO | 8.07 | 8.66 | 4.77 | 8.73 | 5.94 |
| CaO | 11.55 | 9.64 | 7.94 | 9.03 | 7.64 |
| $Na_2O$ | 2.73 | 2.24 | 5.01 | 2.33 | 3.50 |
| $K_2O$ | 2.61 | 3.70 | 1.40 | 1.40 | 1.43 |
| $H_2O+$ | 1.20 | .61 | .63 | .90 | 1.68 |
| $H_2O-$ | 1.50 | 2.77 | 4.58 | 1.10 | .24 |
| $P_2O_5$ | .62 | 1.01 | .88 | .40 | .51 |
| $CO_2$ | 2.14 | 2.48 | .56 | .50 | .41 |
| S | tr. | — | — | — | — |
| Rest | — | .65 | .63 | — | — |
| | 99.81 | 100.06 | 100.42 | 99.86 | 100.88 |

5. Monchiquite, Port nan Gadan, Losset, Kintyre, Anal: W. H. and F. Herdsman.

F. Nepheline ouachitite, Kilchattan, Colonsay. "The Geology of Colonsay and Oronsay, etc.," *Mem. Geol. Surv.*, 1911, p. 46.

G. Monchiquite, Camas an Fhais, Argyllshire. "The Geology of the Country near Oban and Dalmally," *Mem. Geol. Surv.*, 1908, p. 128.

6. Basalt (cf. Dalmeny), Cnoc nan Gabhar, W. of Killellan, 5 miles S.W. of Campbeltown, Kintyre, Anal: W. H. and F. Herdsman.

H. Olivine Basalt (Jedburgh type), Little Caldon, Kilpatrick Hills. "The Geology of the Glasgow District," *Mem. Geol. Surv.*, 1925, p. 182.

The resemblances between the Machrihanish monchiquite and the Colonsay nepheline ouachitite (columns 5 and F, Table 2) are very striking, practically the only difference being an excess of about 2% CaO and a deficit of 1% $K_2O$ in the former. The chief disagreement between the Machrihanish rock and the average monchiquite of Daly (*loc. cit. p.* 36) is that the latter has more $SiO_2$, $Al_2O_3$, and alkalies and less iron, MgO, and CaO. Both the Argylshire rocks shown in columns F. and G. have less CaO than either the Machrihanish or average monchiquite. The analysis shown in column G has markedly less CaO and MgO than either of those shown in columns 5 or F.

In columns 6 and H the Cnoc nan Gabhar fine-grained basalt is compared with the jedburgh basalt which is intruded into the Little Caldon Neck, N. of the Kilpatrick Hills. The remarkable

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agreement between the two, one of which is definitely known to be of Carboniferous age, makes it possible that the Cnoc nan Gabhar intrusion may be of Carboniferous age also, although from want of evidence (since it cuts metamorphic rocks only), it has been described under the Kainozoic intrusive rocks.

TABLE III.

Norms of New Analyses (numbered as in Tables I and II).

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Quartz .. .. .. | 15.60 | 4.08 | 9.24 | 9.36 | — | — |
| Orthoclase .. .. | 22.24 | 26.13 | 21.68 | 25.06 | 15.57 | 8.34 |
| Albite .. .. .. | 36.68 | 39.82 | 36.68 | 36.68 | 6.81 | 19.39 |
| Anorthite .. .. | 10.29 | 12.23 | 14.18 | 14.46 | 15.57 | 31.14 |
| Nepheline .. .. | — | — | — | — | 8.80 | — |
| Corundum .. .. | 1.33 | — | 2.04 | — | — | — |
| Diopside .. .. .. | — | .92 | — | 1.99 | 19.43 | 6.52 |
| Hypersthene .. .. | 8.66 | 10.44 | 6.50 | 3.42 | — | .99 |
| Olivine .. .. .. | — | — | — | — | 11.03 | 21.02 |
| Magnetite .. .. | 3.02 | 1.86 | 6.26 | 4.41 | 5.17 | 3.02 |
| Ilmenite .. .. .. | — | — | — | .76 | — | 5.17 |
| Haematite .. .. | — | — | .32 | — | — | — |
| Calcite .. .. .. | — | — | — | — | 4.90 | 1.1 |
| Apatite .. .. .. | .34 | .34 | .34 | .34 | 1.34 | 1.34 |

1. I (II). 4″. 2. (3) 4.
2. I (II). (4) 5. 2. 3 (4).
3. (I) II. (4) 5. 2″. (3) 4.
4. I (II). (4) 5. 2. 3 (4).
5. III. 6. 3. 3 (4).
6. (II) III. 5. 4. 4.

## PART II.

### Northern Kintyre.

### (Preliminary Statement).

Northern Kintyre is that part of the peninsula north of the N.W.—S.E. line through Campbeltown defined as the northern limit of Southern Kintyre.

The occurrences of rocks younger than the schists are few and scattered, and occur along the E. and W. coasts and around the southern termination of Northern Kintyre, i.e. on the slopes immediately N. of the laggan between Campbeltown and Machri-

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hanish. Since the rocks are so scattered it will be found most convenient to describe them in sections according to the locality where they are found.

According to this classification there are six areas where Old Red Sandstone and Carboniferous rocks occur. These are,

1. Macringan's Point; near the entrance to Campbeltown Loch and N.W. of Davarr Island.

2. Peninver-Smerby; the shore section from the mouth of the small burn N. of the school, New Peninver, and S. of Glen Lussa Water, to the shore E. of Kilchousland.

3. Aucha Lochy and Knockruan Loch; one mile N. of Campbeltown.

4. Auchaleck; N. of Drumore on the main road one mile N.W. of Campbeltown.

5. Bellochantuy N. to Dalkeith.

6. The district N. and S. of Muasdale, from the bend in the road at Stac a'Crochain (or Stac a'Chagair) to Sgeir an Roin, a little N. of Killean.

1. *Macringan's Point.*

(*a*) *Upper Old Red Sandstone.* Red sandstones with quartzite pebbles, and cornstones.

(*b*) *Calciferous Sandstone lavas.* Fine grained and beautifully columnar basalts with tuffs and cornstones. The columns of the lavas are separated from each other by sandstone and red iron oxide, sometimes as much as a foot across in places.

The lavas are chiefly jedburgh basalts with good ophitic texture but sometimes with microlitic augite. Microphenocrysts of olivine are represented by green and yellow and dark brown pseudomorphs.

2. *Peninver-Smerby.*

(*a*) *Peninver Section.* The Palaeozoic rocks here consist entirely of L.O.R.S. and their relations and characters are best seen from the accompanying diagram (fig. 22).

In these areas the basal breccia is seen lying directly upon the schists and filling in irregularities in the pre-O.R.S. land surface.

(*b*) *Smerby Waterfoot Section.* Basal breccia, red sandstone, conglomerate of quartzite and black crystalline limestone.

Red sandstones occur on the shore below Kilchousland.

3. *Aucha Lochy and Knockruan Loch Section.*

(*a*) L.O.R.S.: Conglomerate of quartzite boulders, and white sandstones with many spots of iron oxide are seen W. of the quarry S.W. of Knock Scalbert and continuing northward along the western side of Aucha Lochy. To the E. of Knock Scalbert are gritty white sandstones.

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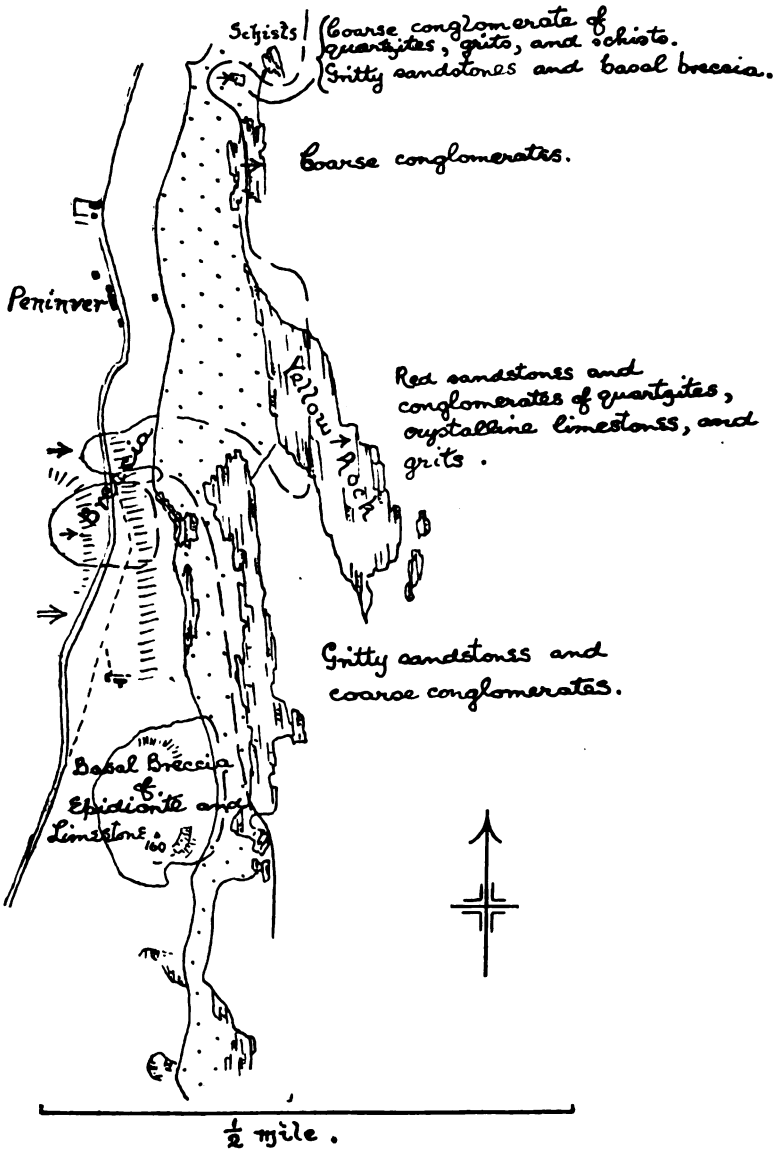
Schists
Coarse conglomerate of quartzites, grits, and schists.
Gritty sandstones and basal breccia.
Coarse conglomerates.
Peninver
Red sandstones and conglomerates of quartzites, crystalline limestones, and grits.
Gritty sandstones and coarse conglomerates.
Basal Breccia of Epidiorite and Limestone
½ mile.

Fig. 22.—Peniver Section of the O.R.S.

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(*b*) U.O.R.S.: A small exposure of quartz conglomerate is seen on the old road just S. of the ruins of Auchalochy. To the E. overlying the gritty sandstones of the lower division is a band of cornstone.

(*c*) *Calciferous Sandstone*: Dark fine grained lava, extremely platy and well jointed with much calcite and malachite along the joint planes. On the southern side of Knock Scalbert and just N. of the fault separating the lavas from the Dalradian limestones and epidorites, the lavas are much broken up into a rock resembling an agglomerate. With the fine grained varieties on the northern side are associated many vesicular types.

Intruded into these lavas is the agglomerate of the neck on the southern shore of Knockruan Loch. Boulders in this neck are generally small and consist of Carboniferous intrusive rocks and lavas with rounded boulders of quartzite.

4. *Auchaleck Section.*

Conglomerates of quartz pebbles (with subordinate schists and chert) and sandstones of U.O.R.S. dipping at 5° to the E. Exposures are few and difficult to find as there is a thick coating of boulder clay over the whole area.

5. and 6. *Bellochantuy and Muasdale.*

Bright red ochreous sandstones and schist breccia of U.O.R.S. age resting directly upon the metamorphic rocks. The sandstones are false-bedded and bands of conglomerate are common. To the south of the Muasdale section cornstones are found. All these rocks are for the most part lying horizontal and when inclined they are dipping at low angles to the W. A boulder of haematite was found in the breccias on the shore of Muasdale.

## CONCLUSIONS.

From the foregoing description of the rocks of Southern Kintyre it is seen that the area is more or less similar to other areas in the Firth of Clyde and Midland Valley and it will be sufficient to compare it here with the islands and shores of the Clyde estuary.

(1) *The Old Red Sandstone.*

Beginning with the igneous rocks of O.R.S. age these have been briefly described by Geikie (Q.J.G.S., xlviii, 1892, Presidential Address, and "Ancient Volcanoes of Great Britain," 1897) and some points in his descriptions may usefully be considered. In his presidential address to the Geological Society he describes



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eight distinct and independant clusters of volcanic vents ranged along the length of the Midland Valley for a distance of 150 miles. The seventh of these he describes thus: " (7) At the extreme south of Cantire another display of volcanic rocks of Lower Old Red Sandstone age may be studied. Beds of andesitic lavas with tuffs and massive conglomerates overlie the schists of that region and are themselves unconformably covered by the volcanic series of Lower Carboniferous age."

As stated here, however, no lavas have been found in the L.O.R.S. of this tract of country, but beds of extremely coarse agglomerates and conglomerates, and beds of tuffs are common in the two main masses of these rocks, viz.—W. of Southend and to the E. of the area in general (including the island of Sanda) Even more abundant than typical agglomerates are beds in which all the igneous materials are perfectly rounded, and which were laid down as conglomerates.

Closely associated with these relics of igneous activity are the volcanic necks at Southend which have been described. On the shore at Keil Point the small necks are made up of both rounded and angular boulders of biotite-felspar-porphyry similar to the boulders in the surrounding conglomerates (see section on O.R.S. pebbles). As previously stated this led Geikie to believe that these vents were contemporaneous with the rocks into which they are intruded and that the rounded boulders from the conglomerates were shattered and separated from the matrix by volcanic energy mainly because they were not consolidated enough to resist and break as a whole. The area around the vents is extremely faulted and to the W. of the most westerly neck large masses of sandstone are found tumbled about in all manners and recemented together. That the volcanic activity was recurrent is evident from the interstratification of the agglomerates with normal sandstone. Geikie (loc. cit. p. 314) states: " I have never seen anywhere, better proofs of volcanic explosions contemporaneous with a group of strata and of the distribution of volcanic fragmentary material around the vent. A further point of much interest is the additional evidence furnished by this shore section of considerable wave-action during the accumulation of the coarse conglomerates. To give to blocks of porphyrite two feet in diameter a smoothed and rounded form must have required the action of water in considerable agitation."

Cnoc Garbh, which also represents the remains of a L.O.R.S.

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volcanic neck, is filled with a finer and more fragmental type of agglomerate than the Keil vents, and indicates more explosive action than accompanied the smaller ones.

In the O.R.S. of Kintyre, therefore, it is found that there are several distinct types of agglomerates. First there is the normal angular and compact agglomerate of the volcanic necks, as in Cnoc Garbh. Secondly there is the agglomerate consisting of both rounded and angular boulders of igneous rocks (and often quartzite) as in the Keil Point necks. In the bedded agglomerates surrounding these latter, rounded masses up to four feet across are common. In the island of Sanda there are thick deposits of fragmental rocks composed of large rounded igneous boulders embedded in fine grained volcanic materials. In every respect but the rounded nature of the contained boulders these deposits resemble normal agglomerate and indicate, perhaps better than the sections on the mainland which he described, what Geikie cited as a good example of the action of water in considerable agitation on contemporaneous volcanic rocks.

Since it has already been stated that lavas of O.R.S. age are lacking in Kintyre we must look for descriptions of these rocks from other areas of the Caledonian basin to enable us to compare them with those remnants of the lavas which make up so important a part of the conglomerates of Kintyre. Tyrrell's paper on the Petrography of the Carrick Hills[1] furnishes us with a summary of the lava types and describes an area not very far removed from that which we are at present considering. From his summary we see that the main extrusive rocks of the O.R.S. consist of pyroxene-, hornblende-, and biotite-andesites, basalts, trachytes (Pentland Hills), rhyolites and (or) felsites. In Southern Kintyre the series of large rounded boulders of igneous rocks contained in the conglomerates gives an idea of the composition of a series of volcanic rocks which, if it existed in Kintyre, was denuded away during the formation of the conglomerates, or which must have existed outside the present area in a district now under water. Moreover, these boulders consist chiefly of hornblende- and biotite-andesites with rhyolite or dacite (p. 102).

(2) *The Physical Conditions under which the Old Red Sandstone was Deposited.*

To discuss the literature or even give a statement of the various theories and their modifications which have been put forward

[1] *Trans. Geol. Soc. Glasgow*, xv, 1, 1912-13, pp. 42-61.

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to explain the mode of deposition of the vast masses of the O.R. conglomerates would be outside the bounds of this paper. I must not leave the subject, however, without giving some of the conclusions arrived at and stating those which in my opinion, best agree with the nature of these deposits in Southern Kintyre.

P. Macnair[1] in his presidential address to the Geological Society of Glasgow makes no mention of the O.R.S. of Kintyre though he mentions other and much smaller outliers on the northern side of the Highland Border. His conclusions as to the age of the ancient platform upon which the O.R. was deposited are interesting and have a close bearing on Kintyre problems. He says (p. 107),

" In a word we may look upon the Scottish Highlands as the basal wreck of what was in pre-O.R.S. time a great mountain chain, the superstructure having been completely removed by denudation, and it is necessary before we can form a picture of the physical feature of the ancient continental area upon which the later Deutozoic rocks of Scotland were accumulated that we should determine as far as the evidence will permit at what time, and to what extent, this denudation had taken place before the Old Red Sandstone rocks came to be accumulated."

On p. 111 he continues, " the recent discoveries made along the Highland border and in the Glencoe and Ben Nevis districts all go to show that the Highlands must have been covered by a mantle of rocks the basal members of which were probably of Downtonian and Lower Old Red Sandstone age, and it is to this age that we must refer the date of the Highland plateau of marine and sub-aerial denudation."

Prof. A. M. Davis[2] disagrees (and rightly I believe) with Macnair's earlier statement[3] of this view of the age of the Highland peneplane. The peneplane which is so remarkable a feature of the Scottish Highlands was produced after the post-O.R.S. deformation and probably long after, and, as a whole, it must differ from the O.R. floor, because the latter was generally deformed after the O.R.S. was laid down. Davis believes that the peneplane of the Scottish Highlands can hardly have been longer exposed to dissection than since the latter part of Mesozoic time. Tertiary time alone may have been sufficient for the excavation of the narrow glens in the Highlands, as well as for the more general denudation

[1] *Trans. Geol. Soc. Glasgow*, XVII, 1919-22, pp. 105-145.
[2] *Geol. Mag.*, IV, 3, 1896, pp. 525-528.
[3] *Geol. Mag.*, IV, 1896, pp. 106, 217, and 570.

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of the weaker rocks of the the Lowlands. "It is, therefore, not unreasonable" he says "to regard the broad denudation by which the Highland peneplane itself was formed as having been completed in Cretaceous, or, at earliest, in Jurassic time."

This is a point of considerable importance in relation to the mode of origin of the O.R.S. Macnair's own view, which may be stated at this point, is that O.R.S. and Devonian in their respective littoral, shallow-water, and deep-sea deposits represent the one Devonian system which is marine.

It has already been pointed out in this paper (see Tectonics) that the high ground of the Mull of Kintyre was in existence in O.R.S. times much as it is to-day and that the deposits of that age were laid down upon its north-eastern and south-eastern flanks. From my study of Northern Kintyre I find that the general disposition of the high ground of this area differs little from what it did in O.R.S. times. The Old Red breccias, conglomerates, and sandstones are found on the western and eastern coasts laid down in hollows in the schists and against steep, cliff-like bluffs of similar rocks in other parts. Thus Kintyre at that period consisted of two masses of high ground, one long and narrow with steep sides stretching N.E.—S.W. (and including northern Arran) and the other to the S.W. stretching S.W. into northern Ireland. Around these masses of mountains were being laid down vast accumulations of sand, gravel, and boulders, but the low ground between them was not so low as it is at the present day for the strata have been thrown down by Kainozoic faults.

The O.R.S. in the N. of Ireland was laid down upon the south-eastern flanks of the high ground just as we find it in Kintyre and the resemblances between the two sides of the North Channel at this point are so striking as to have led Hull (in the preface to the Explanation of Sheet 14 of the Geological Survey of Ireland, 1886) to state that "it is not improbable that there was originally, if there is not actually, a physical connection between the conglomerate masses on both sides of the straits," for in both areas we find the metamorphic rocks unconformably overlain by massive conglomerates of L.O.R.S. age which are composed of fragments of these rocks.

Similarly in other areas of Scotland we have high ground with deep glens running through it as in Kintyre. In U.O.R. times we had remarkable valleys in the eastern part of the Southern Uplands, especially in the Cheviots and Lammermuirs, which

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are full of O.R. conglomerates, and they mark the course of deeply eroded valleys which in some cases (Landerdale) drained S. and in others (Gifford and Fala) opened northward. Bailey[1] states " they take us back, probably to the time when the Central valley was originated as a structural feature directly influencing the scenery, a true rift valley in fact, recalling that which at the present day includes the Great Lakes of Africa." Reference will be made later to these but I go further than Bailey in believing that the Midland Valley of Scotland existed as a true rift valley when the L.O.R.S. was being deposited.

The most recent paper on the O.R.S. of the Firth of Clyde is Stark's " The Red Sandstones of Toward."[2] Stark believes that these red sandstones were laid down under conditions similar to those which now exist in the northern Sahara on the flanks of the Atlas Range. He describes how deposits of calcium carbonate are formed in shallow temporary lakes called shatts. These lakes are formed in the desert sand by the increased rainfall during the rainy season and having no outlet to the sea they are soon evaporated. To me it seems that the analogy with the Indian kankar deposits is more suitable than Stark's lakes to explain the presence and mode of disposition of nodules, or of lenticular beds, or of massive beds of cornstone within great deposits of conglomerates, breccias, or sandstones. The presence in these of material such as the present day kankar shows that not even the conglomerates of large rounded boulders are of marine origin, but that they are analogous to deposits of some of our greatest rivers—deposits which are essentially terrestrial and which are exposed for long periods to arid conditions.

Stark says (p. 172) that the Toward sandstones are composed of " minute, well-rounded, polished and apparently wind-blown grains of quartz strangely interstratified with occasional irregular patches of coarse, sub-angular breccia, while in other places the sandstones are sufficiently argillaceous to develop sun cracks."

These U.O.R.S. rocks, however, in spite of the misinterpretation of their history by Stark were laid down *as fluviatile deposits during climatic conditions which were never desert in character.*

If the siliceous limestones of Toward were formed by evaporation of desert lakes we would expect to find deposits of salt and gypsum

[1] Geol. of East Lothian, *Mem. Geol. Surv., Scotland*, 1910, p. 10.
[2] *Trans. Geol. Soc. Glasgow*, XVII, II, 1925, pp. 169–172.

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with them, but these cornstones are not different from cornstones from other regions in the Old Red Sandstone. Further, I consider that the sandstones would not be argillaceous if they were of desert origin, and finally, irregular patches of coarse, sub-angular breccia (evidently scree accumulations) seem conclusive proof of the fluviatile nature of the deposits. The whole deposit resembles the Upper Old Red of Fife which with its fish scales still further supports the fluviatile theory.

Maufe has described[1] sandstones of Mesosoic age from Morvern (near Kinlochaline) which contain limestone nodules of a pale grey or white colour and having the irregular nobbly surface of O.R.S. cornstones. The cornstones of Southern Kintyre possess this nobbly surface to a marked degree, and good examples can be seen at Rudha McShannuich (Southend), at Killellan, and at the Galdrings (W.S.W. of Machrihanish). These nodules, Maufe points out, closely resemble in form and disposition within the bed, the limestone concretions found in superficial deposits of many tropical lands. They are widely known as kankar in India and are formed by the evaporation of subsoil water or when this percolates to the surface and loses some of its dissolved $CO_2$. They are, therefore, thoroughly characteristic of terrestrial deposits. With a continuation of the process of deposition the limestone nodules become cemented together into a continuous, or more often into a lenticular, bed of limestone. Lenticular cornstones are characteristic of Southern Kintyre, and such beds may occur among extermely coarse conglomerates of the lower division of the O.R.

In other cases, as in the U.O.R. of the Galdrings, at Kilwhipnach, and at Killellan, the characteristic feature of the cornstones is their great thickness, so that these deposits indicate prolonged terrestrial conditions and a semi-arid climate The sub-angular L.O.R.S. breccia described in this paper as forming the eastern half of Sanda also indicates continental conditions, while rocks described by me in the field as "cornstone conglomerates," which are sandstones with abundant nodules of limestone, seem to resemble closely those described by Maufe from Morvern and therefore point, perhaps even better than the massive beds of similar rocks, to the climate of the time being arid for at least a portion of the year.

[1] *Summ. Prog. Geol. Surv.*, Scotland, for 1909; 1910, p. 35.

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Barrell states[2] that deposits similar to kankar occur in Mexico as granular impure limestone, called caliche, and that in the western United States sands and gravels cemented by lime, chiefly at the upper level of ground water, are known as mortar beds. $CaCO_3$ is also precipitated from solution by evaporation in the deltas of the Rhine and Rhone, where, although the climate is relatively humid, the water, coming as it does from limestone regions, is correspondingly richer in dissolved salts.

The cornstones in the O.R.S. were formed by evaporation of water which flowed from the crystalline schists of the Highlands and which was not overburdened by the amount of calcium carbonate in solution. To precipitate the latter as a soil cement would, therefore, require a climate of semi-arid conditions.

The present writer believes that the O.R.S. is of the dominantly fluviatile origin first[3] advocated by Barrell.[4]

(*a*) *Fluviatile Characteristics of the Kintyre O.R.S.*

The Lower O.R.S. consists chiefly of extremely thick deposits of coarse conglomerates. The boulders in these conglomerates may reach as much as 4 or 5 ft. in diameter, sometimes more, yet they are perfectly rounded. The thickness and wide extent of these deposits is proof that they are not of marine or lacustrine origin. The only deposits of a similar nature forming at the present day are the floodplain accumulations of our largest rivers, such as the Himalayian or Rocky Mountain rivers. The size of the boulders forming these conglomerates indicates that they have not been laid down by ephemeral streams but by rivers of great strength and in considerable agitation.

The sandstones are essentially of a red colour and though the red colour of a deposit is not in itself a sure sign of terrestrial origin, yet, in a case like the present, it undoubtedly strengthens the other factors.

These sandstones are false-bedded but the false-bedding is that of rivers and not of sand dunes.

Dessication cracks and rainprints also occur, and these are signs of floodplain origin.

Flaggy sandstones and cornstones are typical of such deposits.

(*b*) *Earth Movements During the Old Red Sandstone.* During

[2] *Bull. G. S. Amer.*, 27, 1916, p. 360.
[3] See J. W. Evans, *Science Progress*, No. 48, 1918, pp. 639-640.
[4] *Op. Cit.*, pp. 345-386.

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the accumulation of the conglomerates of L.O.R. age in Kintyre small explosive volcanoes were active.

Such vast accumulations of coarse sediment as we find here could only have taken place with subsidence of the area where the sediment was being laid down and with uplift of the mountains to the N. and N.W. to furnish that material. At the end of the period earth movement continued and sub-aerial denudation acted upon the deposits. With the increase in thickness of the sediment the rivers were losing their power to carry coarse material and at the end of the Lower, and practically throughout the U.O.R.S., sandstones are the characteristic deposit.

(*c*) *The Old Red of the Glasgow District.* A comparison of the O.R.S. deposits of the Glasgow district with those of Southern Kintyre is exceedingly interesting and shows the widespread resemblances of these rocks and of the conditions under which they were laid down.

The L.O.R. in both areas is remarkable for the abundance of pebbles and boulders of igneous rocks in the conglomerates, and for the fact that all the pebbles examined are of rock types characteristic of the volcanic activity of the same period and represented by the volcanic group so typically developed in the Ochills. The deposits, therefore, represent the waste of the western continuation of this group.

In the Glasgow district the U.O.R.S. is subdivided into three, which in descending order are,

(3) White siliceous sandstones, conglomeratic towards the base and with bands containing cornstone concretions.

(2) Red, purple and white sandstones, with bands containing cornstone concretions.

(1) Red sandstones and quartz conglomerates, with very subordinate red marls.

The Kintyre sub-divisions are practically similar. They are,

(3) White sandstones and conglomerates, with important cornstones.

(2) Red sandstones, with red clays or marls, and cornstones.

(1) Quartz conglomerates and sandstones.

The pebbles in the conglomerates of this group are composed of Dalradian rocks in general, vein quartz, quartzite, and schists, and the igneous rocks, which form so large a part of the lower division, are, in the U.O.R. of Kintyre and of the Glasgow district, conspicuous by their absence.

(*d*) *Irish Lower Old Red Sandstone.* The L.O.R.S. of northern Ireland, like that of Southern Kintyre, is characteristically a

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conglomerate deposit. The pebbles composing the conglomerates consist chiefly of vein quartz, quartzite, and "felstone porphyry." These boulders are well rounded, and vary in size from a few inches to three, or even four feet in diameter. There are also red and brown (and subordinate white) false-bedded and flaggy sandstones. As in the Kintyre L.O.R.S., the beds nearer the base of the deposit are more conglomeratic. Higher up they are more sandy in character, and the coarser varieties are breccias of igneous rocks.

(3) *Calciferous Sandstone Lavas.*

The correlation of the Lower Carboniferous igneous rocks of Bute and the Cumbraes with those of Arran and the southern end of Kintyre has always been looked upon as being as obviously correct as their correlation with the mainland lavas of N. Ayrshire and Renfrewshire. A study of the Kintyre rocks adds nothing which disproves this linking up of the mainland and islands of the Clyde estuary with the peninsula itself. Southern Kintyre forms part of Geikie's Clyde Plateau which was not confined to the mainland but stretched across the islands in the Firth of Clyde. There are differences in the composition of the lavas and intrusions in these areas.

Geikie states that from the poor development of Lower Carboniferous rocks in Arran it is evident that they were not far from the western or north-western limit of the plateau and a similar conclusion is reached by Smellie from his study of South Bute. Smellie states[1] "A study of the morphology of the Bute lavas makes it clear that Bute must have formed the northern limit of the Clyde Plateau. The necks are numerous and small, flows are thin and limited in extent, and it is higly improbable that the main mass of lavas of the south end of the island were ever continuous with the small outliers to the north. No necks pierce the intervening miles of Old Red Sandstone, and none of the necks or flows in the lava areas suggest power to link up the different districts; so that the conclusion is come to that those outliers are not merely outliers of denudation, but outliers from the Carboniferous vulcanicity lying off the north-western margin of the plateau."

In Southern Kintyre there are two disconnected tracts of Carboniferous lavas, that to the E. of Southend and the larger area stretching N. and N.W. from Killellan. In all that area there is

[1] *Trans. Geol. Soc. Glasgow*, xv, iii, 1914-15, p. 358.

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only one very small volcanic neck of Carboniferous age, and it would have been altogether unable to furnish the lavas. It occurs associated with a basaltic intrusion S. of Killypole farm and W. of Killypole Loch. On the shore at the Slip Rock, Machrihanish, is a small mass of agglomerate, not more than a dozen yards in its greatest extent, which I interpret as a small vent.

In Northern Kintyre there are two disconnected areas of lava, the larger of which is roughly oval in shape, with N.—S. axis a mile in length and E.—W. axis of half a mile. The smaller area is made up of two masses, separated from each other by country disturbed by faulting, but they may have been continuous originally. The most easterly of these occurs at sea-level on Macringan's Point, Campbeltown Bay, and rises to a little over 100 ft. The Knockraun occurrence begins at about 450 ft. and rises to 710 ft. Had all these patches of Carboniferous lava been once continuous with each other, it was not as a continuous sheet of equal thickness, but as irregular flows filling valleys in one place and in others passing over divides between valleys when the latter were filled in. In the central area of the lavas and well exposed on the southern shore of Knockruan Loch, is a vent of agglomerate of the same order of size as the Killypole vent mentioned above and incapable of furnishing more than the masses of lava now occurring in its immediate neighbourhood, if it furnished any at all. Where the sources of the material were it is impossible to say.

As already pointed out (see Tectonics) these lavas are filling in basin-shaped hollows in the O.R.S. and metamorphic rocks. This fact supports the interpretation that the lavas occur at, or even beyond, the margin of the main Clyde plateau, and therefore rest upon a very irregular floor of older rocks.

In Bute, the Carboniferous lavas consist of markle, dunsapie, craiglockhart, and jedburgh basalts, and bostonites. In the Cumbraes they consist of markle basalts and mugearites, with basaltic mugearites and the bostonites and trachytes, which in Bute occur as lava flows, are found only as intrusions. Among the intrusions of this age in the Cumbraes are basalts, bostonites, keratophyres, and felsites. In Kintyre the lavas of Calciferous Sandstone age consist of jedburgh and markle basalts, with dunsapie and craiglockhart types and trachyandesites and soda-trachytes. No mugearites have so far been found. The intrusive rocks of the same age are essentially of the keratophyre-bostonite series, and the intrusions themselves are of large size and very

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abundant. There is a gradual passage from the acid varieties into the more basic through trachyandesites. In S. Bute " the lavas and minor intrusions constitute a series which ranges from bostonite, at the acid end to craiglockhart baslts at the basic end, and those two end types are linked up by intermediate rocks giving practically a continuous series. The mugearites, markle and jedburgh basalts are intimately connected by numerous insensible gradations, and markle basalts pass imperceptibly into dunsapie types by the appearance and increase of augite phenocrysts. The most pronounced gaps in the series occur next the two end members; no intermediate types have been found to connect dunsapie with craiglockhart, and the same applies to mugearite and bostonite."[3] In Kintyre, as I have pointed out, the acid rocks are connected with the basaltic types through trachyandesites and between the keratophyre group and the trachyandesites is a series of soda-rich lavas which I have called albite-trachytes. These intermediate varieties are better developed in Kintyre than in the islands of the Firth of Clyde.

No statement as to the sequence of the lavas is made until a further investigation is carried out.

(4) *Kainozoic Igneous Rocks.*

The southern end of Kintyre is remarkably free from Kainozoic N.W. dykes, and those that are found are poor representatives of the group, for they are small and cannot be traced far. This fact is very remarkable. A glance at the map showing the distribution of Kainozoic dykes in the S.W. Highlands in the memoir on the Tertiary and Post-Tertiary Geology of Mull (1924, p. 357) shows the segregation of these dykes into two great bundles which have been called the Mull and Arran Swarms. The latter begins in Islay and southern Jura, crosses Gigha and the northern part of Kintyre, and so passes on into Arran. In Kintyre these dykes are found from Skipness, where they are fairly abundant, to Saddell and Muasdale. S. of the line joining these two latter districts their occurrence is, as has been noticed above, very sporadic. Now it seems impossible that the dykes found between Muasdale and W. Loch Tarbert represent the whole of this swarm as it is represented in Islay and Jura. The Jura and northern Islay rocks can be followed across Kintyre, but it seems that something must happen to cause these dykes in the remaining

[3] Smellie, *op. cit.*, p. 360.

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and by far the greater part of Islay to die out before they reach Southern Kintyre and the southern portion of Northern Kintyre.

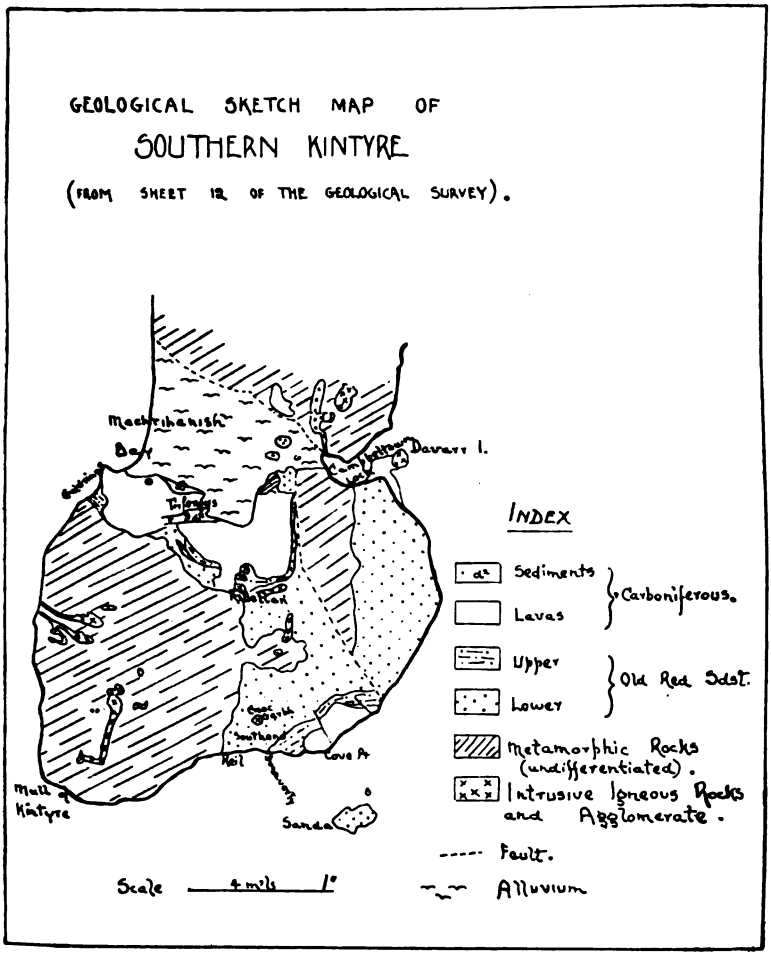


Fig. 23.

The intrusions of Kainozoic age which have been described in this paper are chiefly crinanites and olivine dolerites in general. Additional types, of which it is impossible to fix the age but which have been assigned to this period of igneous activity, consist of monchiquite and fine-grained basalts.

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## ACKNOWLEDGMENTS.

Before leaving the present work, which represents the first connected account of Southern Kintyre since the publication of the survey by Symes, with the assistance, and under the supervision, of Peach, I would like to take this opportunity to express my gratitude for the aid which I necessarily obtained from the work of these geologists; and, with so little previous work as they had to help them, I would express my keen appreciation of the masterly manner in which they have represented the geological structure of this region.

In addition I wish to make acknowledgement of the pecuniary help which I have received. The Carnegie Trustees for the Universities of Scotland furnished all the funds for the rock analyses published in this paper. In the third summer of my field work a grant was obtained from the Government Grant Committee of the Royal Society of London for personal expenses in Kintyre, and though most of the work of the present paper had been finished by that time, and I had commenced the structural problems of the schists, it enabled me to revise the geology of the younger sediments and igneous rocks, while carrying on the study of the Dalradians.

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## No. IV.—Note on the Occurrence of a Deposit of Diatomite at Loch Osobhat, Lewis. By Robert Anderson.

(Read April, 1926; issued 1st August, 1927).

The occurrence of this particular deposit has long been known in Lewis, but the only published reference to it is a brief note in a paper read to the Mineralogical Society in 1886, by Prof. Macadam, of Edinburgh. I had occasion to examine the deposit last summer and in the following note will endeavour to bring the information regarding it up to date.

Diatomite is the organic rock formed by the accumulation of numberless siliceous remains of microscopic plants (diatoms); these remains accumulate as a light porous earth in small lochs and peat bogs. The main constituent of the material is silica; but sand, clay, and limonite, are present in most cases.

The Loch Osobhat deposit is situated on the site of a drained loch in the village of North Tolsta, some 15 miles to the N. of Stornoway, and is comparatively small, covering an area of about one acre. The surrounding rock is gneiss, the principal rock in the island.

To prove the nature and extent of the deposit, 25 bores and one small trial pit were put down with the following results. The peaty material which overlies the diatomite was found to vary in thickness from 4 feet at the centre, to 1½ feet or thereabouts at the edge. The diatomite itself was only of any considerable thickness, about 10 feet, in one small area near the centre, the deposit thinning away very rapidly on all sides.

The drainage enters the hollow at the western side, where the deposit was at one time wrought with comparatively little success; it was found to average from 2 to 3 feet in thickness, to be of a light brownish tint, greyish white when dry, and to have no trace of limonite staining. At the northern and southern ends it stretches over the greater part of the area as a thin but comparatively pure layer.

In the pit which was sunk as near the centre as possible, the cover was found to have thickened to four feet and the diatomite

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to ten feet. The material here was full of plant remains, and the topmost layers were stained bright green by organic matter. At the eastern side where the drainage leaves the hollow the diatomite was well seen in a drain which was then being cut. Here it is stained a deep reddish brown due to the large amount of limonite which occurs along with it; eastward the deposit gradually becomes cleaner, the limonite only appearing in patches around the reed stems. The deposit is also contaminated by small particles of sand and mud.

The following is the analysis of an average sample of the material:—

| | |
|---|---|
| Ignition Loss .. .. .. .. | 11.21 per cent. |
| Silica .. .. .. .. .. | 75.01 ,, |
| Oxide of Iron .. .. .. .. | 3.86 ,, |
| Alumina .. .. .. .. .. | 6.32 ,, |
| Lime .. .. .. .. .. | .09 ,, |
| Magnesia .. .. .. .. .. | 1.17 ,, |
| Sulphuric Anhydride ($SO_3$) .. .. | 1.54 ,, |
| Alkalies .. .. .. .. .. | .80 ,, |
| | 100.00 per cent. |

The available quantity of material is very small, being only about 2,000 tons, and although numerous other likely places in the vicinity were examined no further deposits were found. This deposit is interesting as being the only one in Scotland occurring in gneiss, the other known ones occurring in basalts and granites.

The diatoms which occur in this deposit have not been determined.

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## No. V.—The Rarer Detrital Minerals of British Sedimentary Rocks.

By Prof. P. G. H. Boswell, University of Liverpool.

(Read 9th December, 1926; issued 10th September, 1927).

Until comparatively recent years the common sedimentary rocks were regarded as of less interest than igneous rocks from the mineralogical standpoint. This view probably arose from the belief that their constituents displayed a lack of variety. But, although sands, silts, clays and calcareous sediments (with their consolidation products) consist largely of a few commonly-occurring constituents such as quartz, felspar, clay-substance, calcite, dolomite, etc., they are now known to contain also other detrital and authigenic minerals. These, despite their presence in relatively small quantities, show a considerable variety in composition, form, colour and other properties. Such "accessory" minerals are not less important than the corresponding accessory minerals of igneous rocks. Usually they are of greater density than the common minerals mentioned above; they therefore form the "heavy residues" of rocks and make up the bulk of "concentrates" formed by natural or artificial panning. As a rule, they amount to between 0.1 and 0.01 per cent. by weight of the whole; they may, however, in fine sands, amount to as much as 4 per cent., whilst, on the other hand, in gravels, clays and limestones, they constitute much less than .005 per cent. Such heavy detrital minerals may justifiably be termed the rare (but not rarer) constituents of sedimentary rocks. Included among them are all the common minerals (usually known as the "rock-forming minerals") of igneous and metamorphic rocks. Indeed, many minerals of infrequent occurrence in these rocks are now known to be present in sediments. The total number of mineral-species recorded on good authority from clastic rocks (excluding vein-forming and authigenic minerals) is about 160. Many of the heavy minerals are of widespread occurrence in British sedimentary rocks and are therefore of no great value as indicators of origin. In our present state of knowledge, little significance can be attached, for example, to the presence of colourless or dusky



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zircon, brown or grey tourmaline, and yellow or foxy-red rutile. Yet, as indicated below, other varieties of these minerals may be of extreme importance as clues to the source of the detritus containing them. It may also be remarked at this stage that whilst tourmaline may fairly be described as ubiquitous in clastic rocks, the British sediments are richer in respect of this mineral than others of various ages from abroad. The British area of deposition was clearly influenced by distributive provinces (to employ a useful term coined by Dr. A. Brammall) where that mineral occurred abundantly. In these circumstances it is small wonder that the abundance of tourmaline is only equalled at many British stratigraphical horizons by its extraordinary variety of form and colour. I may here cite as examples the Bunter, the Wealden of the Isle of Wight and the Weald, the Lower Greensand generally, the Upper Cretaceous, Eocene, Bovey Beds and Pliocene of the West Country, and the Eocene and Oligocene of the London and Hampshire Basins.

But to return to the general consideration of these rare minerals. We may draw a distinction between commonly-occurring heavy detrital minerals such as iron-ores, garnet, zircon, anatase, rutile, tourmaline, apatite, andalusite, brookite, staurolite, topaz, chlorite, hornblende, epidote, mica and kyanite, and those which are met with more rarely. The latter (the 'rarer' detrital minerals of this paper) occur as single grains, or if they are more plentiful, are of restricted geographical and geological distribution. Such minerals may constitute only one grain in every one hundred to three hundred grains of common heavy detrital minerals, that is, they are present in the proportion of about 1 in 10,000 of the grains of a sedimentary rock and would form about .0001 per cent. by weight of it. Insignificant as such rarely-occurring grains may appear, they often provide more valuable clues to the history of the containing sediments than the more common heavy detrital minerals. Examples of these rarer detrital minerals are pleonaste spinel, fluorspar, cassiterite, corundum, hypersthene (and enstatite), sillimanite, arfvedsonite, glaucophane, dumortierite, monazite, sphene, chloritoid, aegirine, axinite and others. The importance of the distribution of many of these minerals is considered in some detail below. It must be remembered, however, that any one or more of these minerals may be locally abundant; actually, it is their widespread and uniform occurrence, although in very small quantities, which is of greater significance and value.

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The omission of certain common rock-forming minerals from the short lists given above has doubtless been noted. No mention has been made, for example, of olivine and augite. At the present time we know too little of the occurrence of these two minerals in sediments to enable us to generalize. Locally, each is abundant, but inasmuch as each is liable to disappear as a result of its relative chemical instability, the time is not ripe for the basing of conclusions on its presence or absence. The frequency of olivine and pyroxene in present-day shore-sands, old valley deposits and glacial drift, and their rarity in older sediments, supports the view that they have a limited stability in geological time. Neither mineral is always easy to identify with certainty when it occurs as sporadic grains in sediments; thus its presence may frequently have escaped notice. Nevertheless, augite has been recorded from Silurian, Old Red Sandstone, Carboniferous, Permian, Triassic, Cretaceous, Eocene and other rocks; hence, on the assumption that the identifications are beyond question, it has been preserved under favourable conditions.

*Noteworthy Varieties of Common Detrital Minerals.*

Before we pass, however, to the consideration of the rare detrital minerals mentioned above, a few distinctive and easily recognised varieties of the commoner detrital minerals may be noted. While the abundance or rarity of such common species as garnet, muscovite, biotite, tourmaline, andalusite, staurolite, chlorite and hornblende may itself often yield valuable information, there are certain varieties of many of these minerals which are of more than general interest. The distribution of almandine and pyrope, for example, has yet to be worked out in detail. The yellow or green lime-garnet (grossularite) is of much rarer occurrence. At the moment it has been recorded only from the Abberley Breccia,[1] but I have found it in various other deposits. Although its source remains doubtful, there is a likelihood that its occurrence is not as sporadic and haphazard as it appears to be at present, and that in due course the mineral may yield a clue to the source of the sediments.

For many years varieties of the very common mineral, zircon, have been described and figured. Attempts have often been made to refer particular forms (including colourless, dusky, grey, yellow

[1] W. F. Fleet, 'The Chief Heavy Detrital Minerals in the Rocks of the English Midlands,' *Geol. Mag.*, 1925, pp. 98-128. Dr. Fleet kindly submitted his microscopical preparations to me.

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and brown crystals and grains) to sources in definite types of igneous and metamorphic rocks. None of these attempts has proved altogether successful, and it was left for a distinguished Scottish worker on sedimentary rocks, Dr. Wm. Mackie, to place his co-workers under a debt of gratitude by running to earth, in the Lewisian gneiss, the distinctive rose-purple and usually ovoid grains of zircon, long known to occur in British sediments.[1] As an account of British occurrences of this variety has been given more fully elsewhere,[2] it need not be considered further here.

Again, lemon-yellow or foxy-red rutile, in the form of long needle-like or stumpy prismatic crystals or of irregular grains is well known as a common detrital mineral. Whilst the origin of these varieties can usually be placed, it has long been a source of difficulty to some of us to account for the extraordinary quantity present in many sediments. Granting that it is a resistant mineral and may have passed through more than one cycle of deposition, or even that it may be the end-product of transformations of other titanium minerals, and may be in part authigenic, I am still puzzled by its excessive abundance at certain horizons like the Oolites of Yorkshire, the Inferior Oolite and Lias of the West of England, and the Reading Beds, Blackheath Beds, and Bagshot Beds of the London Basin.

But there is another variety about which little has been written, but which is of some interest. What is the source of the deep-red or purplish-red grains, frequently large and irregular and comparatively unabraded, and usually displaying no crystal form? The variety is apparently ferriferous, for it reacts to the electro-magnet, and may have been derived from basic igneous rocks. It is abundant in the Lower Carboniferous Sandstones, the Permian, Trias, Lower Greensand and other deposits. Rutile-bearing igneous and metamorphic rocks are known to be plentiful in the Sc ttish Highlands; the explanation of the abundance of the purple-red variety of the mineral in the Carboniferous and other rocks of the Midland Valley therefore offers an interesting problem for s ome Scottish investigator.

Muscovite, with the usual wide optic axial angle, is plentiful in sediments, but we still await knowledge of the source of the

[1] The source of the Purple Zircons in the Sedimentary Rocks of Scotland, *Trans. Edinburgh Geol. Soc.*, vol. xi, 1923, pp. 200-213.

[2] 'On the Distribution of Purple Zircon in British Sedimentary Rocks,' *Mineralogical Magazine*, vol. xxi, 1927, pp. 310-317.

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colourless or pale-green mica with a low optic axial angle. We have yet to determine whether this variety is too definite in its characters and too constant in its occurrence at certain horizons, to be regarded as a bleached biotite. For example, it is a characteristic mineral of the peculiar assemblage of the Lenham Beds (Lower Pliocene)[1] and is found also in the Lias-Inferior Oolite of the West and Midlands of England, as well as at other horizons. I have been surprised to find it so rarely in the micaceous sandstones of the Scottish Lowlands, my only records being from Arran and Crofthead. Intensive work will doubtless prove it to be more widespread.

In British sediments, tourmaline occurs in irregular grains and crystals of varied form, and of almost every conceivable colour. We cannot hope that the grey, yellow and brown varieties will ever be traced to particular sources, but the rose (rubellite), blue, indigo (indicolite) and green grains are of more restricted occurrence in sediments and may in due course be utilized as indicators of the source of the detritus. In the west and south of England, the post-Carboniferous granites and their pneumatolytic aureoles yield abundant blue and indigo tourmaline, the trail of which, diminishing in definiteness, can be traced eastwards in the Upper Cretaceous, Eocene and Oligocene rocks of the West Country and the Hampshire Basin, and finally into the London Basin.

Andalusite has long been of value as an indicator-mineral, largely because of its possible sources being confined to several areas well-known petrologically (such as Devon and Cornwall, Brittany, the Ardennes, Anglesey, the Lake District, the Scottish Highlands and others). Its usual varieties are the water-clear pleochroic form, and the grains dusky with inclusions, often arranged in bands with or without faint colour and pleochroism. But it is only in recent years that the variety chiastolite, with inclusions arranged definitely in the form of a cross, has been recorded from sediments. The sources of chiastolite, as distinct from ordinary andalusite, around the Dartmoor granite and in Brittany are well-known, and we have no difficulty in explaining the derivation of the mineral in the Bovey Beds and more recent deposits in Devon. Doubtless, also, the chiastolite of the Bagshot Beds of the London Basin had a similar origin, but can the same be said of that of the Lenham Beds

[1] G. M. Davies, 'The Rocks and Minerals of the Croydon Regional Survey Area,' *Proc. and Trans. Croydon Nat. Hist. and Sci. Soc.*, 1915-16, p. 77 etc., and other papers by the same author.

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and also of the Red Crag of Suffolk? In the latter case, the mineral is associated with many minerals suggestive of a source in Central Belgium and the Ardennes.

Similarly with staurolite, the pale golden, rich golden-brown and other varieties full of irregular inclusions may be traced to their sources in Scotland, 'Armorica,' or Belgium, but the variety found by Dr. F. T. Ingham in the Spilsby Sandstone,[1] which occurs also in the Lower Greensand, with zonary and cruciform arrangements of the inclusions, may give more precision to our knowledge of the direction from which it (and its associated minerals) have been derived.

The well-known mineral kyanite assumes many different forms in sediments. It occurs most widely, perhaps, as approximately rectangular fragments (often with re-entrant angles), either sharply angular or somewhat rounded. Examples of this habit in British rocks from the Carboniferous to Recent deposits are too plentiful for enumeration. Less commonly, however, bent cylindrical grains are to be noted as in the East Anglian Box-stones and the Lenham Beds. Grains dusky with numerous fine inclusions are also characteristic of the Pliocene. Carious indented grains are found in the Northampton Ironstone, and wisp-like, fibrous grains in the Inferior Oolite and other deposits. Pleochroism in patchy blue tints is irregular in occurrence. Some of these 'habits' may be the results of subsequent chemical action; others may give a clue to the source of the mineral.

The varieties of chlorite and hornblende met with in sediments are numerous. They vary in colour, absorption, optical orientation and birefringence. To consider them in detail would occupy more space than would be justifiable here. The sudden appearance and local abundance of certain well-marked varieties provide interesting problems for solution. A plea, however, may be entered for the careful recording of the optical characters of these varieties when their occurrence in sedimentary rocks is noted.

*Some Rarer Detrital Minerals.*

We may next pass to the consideration of the rarer detrital minerals mentioned previously. The following records of their distribution in British sedimentary rocks will doubtless be widely extended in the future, but we may reasonably hope that each will still continue to provide a valuable indication of its source.

[1] The Petrology of the Spilsby Sandstone, *Proc. Geol. Assoc.*, vol. xxxviii, 1927, pp.

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*Pleonaste.* Records in sediments of this interesting blue-green spinel are ever increasing, but our knowledge of its original occurrence still appears to be limited.

The earliest record known to me is of a single grain from the Carboniferous Limestone series of Caldwell, Renfrewshire. I have observed this spinel also in the Bunter rocks of Co. Antrim. The mineral is a rare but persistent constituent of the Lias-Inferior Oolite (Bridport-Midford-Cotteswold Sands) of the West of England, and is characteristic of the Northampton Ironstone and associated sediments (also of Inferior Oolite age). It appears once more in the Callovian of Yorkshire and the Upper Kimmeridgian and Portlandian rocks of the southern Midlands and Dorset. It is a characteristic mineral also of the Spilsby Sandstone, and is found, though rarely, in the Wealden and various divisions of the Lower Greensand. From Aptian to early Pliocene rocks, our only records are of very rare grains in all the various divisions of the Eocene, so scattered in horizon and locality as to be of no obvious significance. In the Lenham Beds, however, it reveals itself again as one of the typical minerals. Rare grains are also found in the Glacial and Recent deposits.

*Other Spinels.* Exclusive of magnetite, other spinels are exceedingly rare. Occasionally coffee-brown isotropic grains, possibly referable to picotite, have been found in the Eocene rocks of the northern part of the London Basin, and in the Glacial deposits of the East of England. The record of the occurrence of chromite in the Lower Chalk of Beer Head, Devon, by Mr. G. M. Davies points to derivation from a massif of ultra-basic rocks of the Lizard type. Chromite has also been doubtfully identified by Mr. A. Stuart in the dune-sands of South Wales.

*Cassiterite.* Records of this mineral in British sediments are scanty, and it is possibly more widely distributed than we are aware at present. Unfortunately, the red-brown and yellow varieties are easily mistaken for rutile. The difference in refractive index is not easily recognised and proved with isolated grains in permanent mounts, and pleochroism and zonary structure are not always displayed. The richly-pleochroic variety (warm red-brown to sea-green), so abundant in certain recent foreign sands, is rare in Britain.

The mineral has been found in the New Red Sandstone, Cretaceous, and Tertiary deposits of Devon, its source lying undoubtedly towards the west. It is present in the Pliocene of Corn-

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wall. Many years ago, too, I found scattered grains in the clays and sands of doubtful age filling pockets in the Carboniferous Limestone of Derbyshire. Its source was then a puzzle, for those rocks were situated so far from known occurrences of the mineral. More recently, however, Mr. J. G. A. Skerl has found it in relatively great abundance among the accessory minerals of the Mount Sorrel granite in Leicestershire, and has isolated it by crushing and treatment with heavy liquids. Cassiterite may thus turn out to be a rare constituent of many British granites as well as of British sediments. It has already been recorded in the Lower Greensand (doubtfully by Dr. R. H. Rastall), the Clay-with-flints of Surrey (by Mr. G. M. Davies), and in the dune-sands of South Wales (by Mr. A Stuart), and other recent deposits.

*Corundum.* The occurrences of this mineral are so erratic that it is difficult at the present time to attach any significance to most of them. The beautiful hexagonal grains found in the Upper Eocene sands and clays of Devon doubtless had their origin, like those of the Cretaceous of the Haldon Hills and the Pliocene of St. Agnes, in the metamorphosed and partly-assimilated argillaceous sediments in contact with dyke-rocks in Devon and Cornwall. The mineral has also been recorded from the New Red Sandstone of Devon, but Dr. H. H. Thomas felt some doubt as to its identity. It is recorded in the Pennant Sandstones of South Wales (by Dr. A. Heard), in the Kimmeridgian and Portlandian deposits (by Dr. E. Neaverson), in the Sandgate Beds (by Mr. G. M. Davies). Scattered grains, also, which occur in the various Eocene deposits of the London Basin may have had, like those of Devon, a western origin. The source of the rare grains found in glacial and recent deposits is not conjecturable, since they may have passed through more than one cycle of deposition.

*Sphene.* Several distinct varieties of sphene are recorded from British sedimentary rocks. In the first place, there are crystals of the ' envelope ' and elongated-diamond form and yellow-green or olive-green colour, found by Dr. R. H. Rastall in the Lower Greensand of Aspley Guise in Bedfordshire and Great Gransden in Huntingdonshire. They are very abundant locally and are most beautiful objects. I have never seen them elsewhere, however, although a yellowish form was found by Dr. E. Neaverson in the Corallian of Lamb Inn Quarry, Kingston Bagpuize, Berkshire. This variety is not unlike that from Aspley Guise, but the grains are angular, with sub-conchoidal fracture, and they differ in colour.

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By far the commonest variety of sphene occurring in sediments is in the form of colourless to pale yellow or brown grains. They are usually equidimensional, often sub-rounded, but frequently ragged-edged, as if the prismatic or pyramidal cleavage were in evidence. They are not aggregates, but parts of single crystals, and may be termed 'granular' sphene, for they resemble most the granular variety of the mineral found as an alteration product in igneous rocks, or in contaminated portions of those rocks and in the adjoining altered sediments. A fourth variety has been recorded, namely the coffee-brown or dirty brown form known so well as idiomorphic crystals in granites, syenites and other rocks.

The local abundance of granular sphene, the sporadic occurrence of 'nests' of it, and its association with other titaniferous minerals, render it uncertain at present as an indicator-mineral. Whilst it may be in part authigenic, its frequent association with such minerals as chloritoid, rutile, glaucophane, kyanite and monazite suggests that it may have been derived from the same source as these. Some of the horizons at which it is relatively plentiful are the Bunter, the Keuper, the Middle and Upper Lias, the Inferior Oolite (including the Northamptonshire Ironstone and the beds associated with the Scarborough Limestone), the Callovian, Kimmeridgian, Portlandian, Aptian, Albian, and the Eocene, Pliocene and Glacial deposits generally.

*Monazite.* The first record of the presence of monazite in British sediments was that (by Mr. G. M. Davies) of its occurrence in the Lower Greensand, Lenham Beds, and valley-deposits of Surrey. Dr. H. H. Thomas also noted its occurrence as widespread in British Recent and Glacial sands. Subsequently it was found in the Millstone Grit, the Permian, Triassic and later rocks. The resemblance of the mineral in small isolated grains to yellow zircon, rounded epidote and pale staurolites makes spectroscopic confirmation very desirable.

O. A. Derby and others long ago gave an indication of the widespread occurrence of this mineral as an accessory constituent of granites etc., (e.g. Devon and Cornwall). Dr. Mackie extended our knowledge of its occurrence in the Newer Granites of Scotland and the sediments derived from them. It has since been found in many other granites, including that of Shap. In view of its widespread occurrence in sediments, despite its proneness to abrasion and decomposition, and having regard to the fact that it may, for all we know, be present in most British granites, great

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caution is necessary in indicating its probable source. Nevertheless its relative abundance (and, in rare cases, as at Garngad, excellent crystalline form) in the Carboniferous Sandstones of the Midland Valley of Scotland, where it is associated with purple zircon, staurolite, garnet and rarely, kyanite, points to an origin in the Newer Granites of the Highlands. Its trail into the Millstone Grit and Coal Measures of Yorkshire, Lancashire, Staffordshire and Derbyshire, where it is by no means scarce, points to the same northern origin, but the possibility of reinforcement from the Galloway, Cheviot and Lake District granites should not be forgotten. As a constituent of the Permian rocks of the North of England, its form and condition indicate the possibility of derivation in part from the Carboniferous, although many of the grains are more likely to have been derived directly from granites. It is a rare but persistent mineral in the Triassic sediments of Antrim, Wales, Lancashire, Yorkshire and the Midlands. In these cases, also, it may have resulted from the erosion of Carboniferous or Permian strata, but its freshness and its associates rather point to direct derivation from crystalline rocks.

Its presence in the Lias-Inferior Oolite of the West Country may be attributed to erosion of granites in the old "Armorica," for the accompanying minerals indicate that area as the source. However, in connexion with its occurrence farther north in the Spilsby Sandstone of North Lincolnshire, and in the Callovian of Yorkshire, we are tempted to look once more to Scotland, but the possibility of its derivation from older sediments or from crystalline rocks, exposed or hidden, of the Midlands and East of England or of the Lake District should restrain us. When we come to the Lower Greensand, we find monazite is one of the less abundant, but still persistent constituents of the southern outcrops. How far northwards it extends has yet to be proved. Of its occurrence at this horizon more is said at a later stage. The mineral is not characteristic of later horizons, with the exception of the Lenham Beds. Its persistence here, like that of certain other rare minerals adds to the interest of these Lower Pliocene sediments.

*Chloritoid.* Although this mineral had long been recognised by the Italian investigators as a constituent of the Miocene and later deposits thrown off from the Alps, it was not until comparatively recently that it was detected in British sediments by Mr. J. G. A. Skerl. Except for a single grain found in the Keuper of Warwickshire, on the isolated occurrence of which no conclusions

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can be based, the earliest appearance of the mineral is in the Toarcian-Aalenian sands of the West of England. It is there a persistent rare mineral, but around Yeovil it becomes more plentiful. It is also characteristic of the Northampton Ironstone and associated strata of Inferior Oolite age, and is found, a few grains at a time, all along the outcrop from Stowe-nine-Churches to Greetwell, near Lincoln. It is also present in the Upper Estuarine Series in Yorkshire. Higher in the geological column, it is next found as a rare constituent of the Kimmeridgian and Portlandian of Dorset and Buckinghamshire, and is seen sporadically in the Lower Greensand of Flitwick (Beds.) and other localities. It is present also in the Glacial deposits. Although beyond the British area, its occurrence in the Sables d'Hydrequent, near Marquise in the Boulonnais, is of interest, for the Belgian massif could have yielded ottrelite but not the variety of chloritoid here considered. Its source would therefore seem to have been the same as that of the above-mentioned West Country sands and of the Dorsetshire Portlandian, namely Brittany. The origin of the detrital chloritoid of Northamptonshire is not so easily determined, for this area may have derived its material from Scotland (where the chloritoid is indistinguishable from that of Brittany) or even the old land-mass now buried under Cretaceous and later deposits in the East of England.

*Glaucophane* is a frequent associate of chloritoid in metamorphic rocks (as in Brittany and Piedmont), the exception that chloritoid was present in the Highlands to the exclusion of glaucophane having now been removed by the discovery of the latter mineral in Ben Ledi Schists by Dr. Wm. Mackie. Similarly, the two minerals are frequently associated as rare constituents in sedimentary rocks in areas as widely distributed as Trinidad, the Po Basin and the British Isles. Sediments derived from the glaucophane-schists of Anglesey, however, do not appear to contain chloritoid; moreover, the glaucophane is not so richly coloured as that from other localities mentioned above. The mineral is a rare but ubiquitous constituent of the Lias-Inferior Oolite sands of Dorset and Gloucestershire, of the Northampton Ironstone and other Liassic and Inferior Oolite sediments of the Midlands, and of the Kimmeridgian and Portlandian of the south of England. It has not yet been recorded from the Lower Greensand, but is found sporadically in the Oldhaven and Reading Beds of the London Basin. Lastly, it is present in glacial deposits in East Anglia and

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Durham, in wind-blown (?) loess-like deposits of Guernsey, in the sands of pre-glacial screes in Anglesey, and in the valley-deposits in Surrey.

*Sillimanite.* The relative rarity of sillimanite in sediments is doubtless due to its habit and the ease with which it breaks down mechanically. We have no sediments in Britain, so far as we know at present, like those recent sands from India, for example, in which the non-magnetic heavy crop is largely composed of the mineral. Its occurrences in the Bunter, Upper Lias, Inferior Oolite, Callovian, Thanet Beds, Reading Beds, Claygate Beds, Bagshot Beds, Upper Headon Beds and the Pliocene of East Anglia and Cornwall, as well as more recent deposits in Scotland, Ireland and England, are sporadic and rare. Whilst it is doubtless more widespread than is at present realized we can point only to the Lower Greensand and the Lenham Beds as formations of which it is a persistent, although rare, constituent. In connexion with the occurrence of sillimanite in the Eocene of the London Basin, the Lenham Beds and the Crag of Suffolk, its presence in Belgian Eocene and later sediments is worthy of note.

*Hypersthene.* Apart from its widespread occurrence in Glacial, post-Glacial and Recent deposits (especially in the neighbourhood of hypersthene-bearing igneous rocks, as exemplified by the sands along the coasts of North Wales and Northumberland), hypersthene appears only erratically in British sediments. Apart from Scottish occurrences, occasional pleochroic grains have been recorded from the Carboniferous of North Wales, the Permian of Lancashire, the Trias of the Vale of Clwyd, the Middle Lias, Portlandian, Lower Greensand, Headon Beds and London Clay. Only in the Bunter Sands can it be described as persistent. Doubtless its chemical stability is not great, in which case it may formerly have been more widespread. Further work is desirable before its significance can be appraised.

*Petrographic Characters of Some Interesting British Deposits.*

Some acquaintance, although limited, with the petrographic characters of foreign sedimentary rocks of various ages inclines me to think that the mineralogical characters of British deposits, considered as a whole, are of exceptional variety and interest. This is but a repetition of an old story, for it is well-known that no other area contains, for its size, so great a variety of rocks and minerals of scientific and economic importance as Britain. The explanation of these exceptional features lies, as has often been

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pointed out, in the geological history of British rocks. The area of Western Europe was one of frequent marine transgressions, and the sedimentary succession was dominated from early times by the neighbouring crustal blocks of ancient rocks. Although the 'cores' of these blocks were of pre-Cambrian rocks, later sediments were in turn infolded with them and often metamorphosed in the process, or altered by igneous intrusions connected with the earth-movements. The detritus from these massifs accumulated in our epeiric seas, the shorelines and depths of which were continually in oscillation. The area was influenced, though not so vigorously as to eliminate original petrographic characters and records of life, by practically all the important series of earth-movements or 'revolutions.' These movements emphasized the altitudes of the adjoining land-masses and created to some extent fresh areas of elevated country, which by their denudation, 'rejuvenated' mineralogically the sediments formed from them. Had there been long terrestrial periods in our area, the bulk and variety of our sediments would obviously have been much restricted. On the other hand, protracted geosynclinal conditions would have led to a levelling up of land and sea-floor and a resorting of the sediments,[1] with consequent impoverishment in mineralogical constitution. It is doubtful whether geosynclinal conditions were existent in our area more than once or possibly twice (if the Lower Carboniferous as well as the Cambrian-Ordovician-Silurian be included) during its geological history. The record of the Mesozoic and Tertiary rocks in particular is one of ever-changing position of shore-lines and bathymetrical contours, as is well indicated by the bold attempt of Jukes-Browne to depict the palaeogeography of various epochs.

The presence of detrital minerals, other than those which may be derived from basic igneous rocks, is itself evidence that the sediments containing them are of terrigenous origin. Since all British sedimentary rocks (excepting, perhaps, for the present, radiolarian cherts, the allogenic minerals of which have apparently not yet been investigated) contain such detrital minerals in greater or less abundance, we have an additional reason for regarding them as certainly not of deep-sea (that is, pelagic) origin. This seemingly simple criterion must, however, be used with caution, for the pelagic oozes obtained by many of the deep-sea expeditions contain mineral fragments. Nevertheless, these are found to be

[1] *See* the writer in *Proc. Liverpool Geol. Soc.*, vol. xiv, 1924, pp. 2-33.

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either authigenic, like phosphates and phillipsite, or of volcanic origin, derived doubtless from submarine action. I have discussed elsewhere[1] the various minerals recorded and their significance. The species are mainly those characteristic of basic and sub-basic igneous rocks.

The presence of heavy minerals either of metamorphic origin or derived from acid and intermediate igneous rocks is thus *prima facie* evidence that the sediments were formed, at least in part, from the erosion of continental masses.

It is with the position and constitution of the land-masses from which British sediments were derived that we are here more closely concerned. The dominant areas of elevation were (1) the crustal block including Scandinavia, Scotland and northern and north-western Ireland, (2) the old 'Armorica,' of which Brittany, western Normandy, the Lizard and Start Point areas are remnants (3) the Ardennes-Stavelot-Condroz-Brabant ridges and (4) the ancient land-mass, no longer visible (unless Charnwood, Caldecote, and Barnt Green are its upraised ridges, as seems probable), known to extend under London, part of the Midlands and most of East Anglia, and apparently connected with the Belgian massifs. This buried mass exercised great influence on the distribution, and possibly also on the constitution of British sedimentary rocks from Carboniferous to Cretaceous times, until it was at last covered wholly or in part by our great Albian transgression. The possible influence of this 'platform' of ancient rocks is considered in greater detail in the sequel.

One important area of old rocks has been omitted from consideration in the above outline. It is the worn-down block of Anglesey (with possibly the Bangor and Llanberis ridges). Doubtless this mass is but a remnant of a once much larger region. Unfortunately, we have little evidence of its influence on the constitution of adjoining sedimentary rocks. It is certain that such influence cannot be traced far in the Cambrian, Ordovician and Silurian sediments; moreover, the investigations yet undertaken of the adjacent Old Red Sandstone and Carboniferous Basement-beds indicate that they display much more impoverished residues than might be expected. The absence of Mesozoic and Tertiary rocks in the neighbourhood of the Anglesey mass renders the story incomplete, but we know that in more recent times the peculiar

[1] *Proc. Liv. Geol. Soc.*, vol. XIII, 1923, p. 273.

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mineralogical features of many Anglesey rocks are reflected in the mineralogical composition of the contiguous Glacial and post-glacial sediments.

Apart from these massifs, the various igneous intrusions of the British area may, by the erosion of both the intruding rock and the metamorphic aureoles, have supplied fresh minerals to the sediments then in course of formation. Few intrusions or their aureoles have yet been investigated in the thorough manner adopted by Dr. A. Brammall in the case of the Dartmoor area. In any case it is unlikely that stress-minerals like glaucophane, chloritoid and others would be yielded by such aureoles.

Let us now consider briefly the mineralogical evidence provided by some of the more interesting British horizons, with especial reference to the crustal blocks mentioned above.

The sedimentary rocks of the latter part of the pre-Cambrian Era are, to judge from the results of the small amount of work that has been done on them, of entrancing interest. They were clearly derivatives of the Archaean and their characteristic minerals may be found in the parent gneisses, schists and other metamorphosed rocks. Only when these early sediments have been investigated in more detail will it be possible to attempt to restore the palaeo-geographical conditions.

The older Palaeozoic rocks (Cambrian, Ordovician and Silurian) cannot be regarded as highly interesting from the petrographic standpoint; moreover, we await the results of more extensive research into their constitution. In the present state of knowledge, they appear to be of geosynclinal character, at no time rich in the variety of their detrital minerals and becoming steadily impoverished with decreasing age. The only heavy detrital minerals known from them are garnet, iron ores, zircon, rutile, tourmaline, chlorite, hornblende and white mica.

Such information as we possess of the petrography of the Old Red Sandstone indicates that the ancient masses were re-asserting themselves under the influence of the Caledonian earth-movements and that the sediments were being 'rejuvenated' in consequence. We note here the entry of the predominant garnet suite, which re-appears so often at later periods. The investigation of the mineralogical characters of these rocks in both the Highland border region and the more southern outcrops is full of promise of interesting results, and it is to be hoped that it will soon be undertaken. The Old Red Sandstone of the Scottish Lowlands is by no means as rich mineralogically as might be expected.

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Fortunately, the Carboniferous System has been more widely investigated, although in many areas the petrographic characters are still unknown.

In the Calciferous Sandstone Series, the Carboniferous Limestone Series, the Millstone Grit and the Coal Measures of the Scottish Lowland area, the characteristic and distinctive detrital minerals are garnet, purple zircon, deep red angular rutile, tourmaline, staurolite, and monazite. In addition, pleonaste, sphene, biotite, epidote, hornblende, kyanite, uniaxial mica, chlorite and other minerals occur sporadically. Considerable variation is observed in the relative proportion of the minerals as the deposits are traced laterally and vertically. The apparently irregular distribution of garnet and staurolite, for example, has yet to be explained. The abundance of purple zircon at certain localities (such as in Arran, Auchenheath, Campbeltown, Drumcavil, Garngad, Glenboig, Monkredding, Plean and Pordovan), and also of monazite (at Crofthead, Drumcavil, Garngad, Glenboig, Monkredding, etc.), confirms, if confirmation were needed, the derivation of the sediments from the Scottish Highland area. The rarity of kyanite indicates either that the mineral is unstable in sediments, or that the kyanite-bearing rocks were not exposed to any extent. Chlorite and biotite may have been present in greater abundance originally, but may have proved too unstable to be retained. Chloritoid and sillimanite, if originally present, have apparently disappeared entirely.

We therefore need go no further than the Highland massif for the source of these rocks. As we proceed, by way of either Lancashire or Yorkshire, into the Midlands, the monazite, purple zircon, red rutile, garnet and chlorite persist to such an extent that the Welsh area of Palaeozoic rocks and the islands of ancient rocks in Central England have left no definite impress on the mineralogical character of the sediments. Kyanite does not persist southwards, and staurolite becomes less common, but chlorite is often very plentiful, especially in the Coal Measure. To explain the presence of certain coarser constituents in the Millstone Grit of Yorkshire, Prof. A. Gilligan has assumed drainage from the south-westward extension of Scandinavia, as well as from the Scottish region. In passing, it may be said that the Carboniferous rocks of Northern Ireland resemble petrologically those of the Scottish Lowland area. It is evident, however, that detailed investigation of the various Carboniferous deposits generally is needed before precision can be given to the problems of origin adumbrated above.

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The Permian rocks continue, so far as petrographic characters are concerned, the story of the Carboniferous. They have been investigated in Northumberland, Durham, Yorkshire, Nottinghamshire, Lancashire and Cumberland. Such deposits as have still been retained in the Permian System in the Midlands and also the New Red Sandstone of the south-west of England have also been studied by various workers.

The Permian of the North of England contains similar minerals to the underlying Carboniferous, and may in many instances have been derived from it. There are cases, however, which suggest that the Permian was drawing directly upon the ancient northern land-mass. Staurolite, for example, becomes far more abundant in the Permian than the Carboniferous, although kyanite is strangely rare. Monazite is so soft a mineral that it is unlikely to pass through more than one cycle of erosion and its presence in the Permian points to direct derivation, at least in part. Similarly, the appearance of hypersthene, epidote, chlorite and hornblende is an indication of the existence of land composed of crystalline rocks at no great distance.

So much work has recently been prosecuted on the Triassic rocks that I propose here to pass by their problems. I would only say that whilst some of their detrital material, both as regards pebbles and minerals, has clearly been derived from Permian, Carboniferous or older sediments, the local abundance of such minerals as staurolite, red rutile, purple zircon, chlorite, hornblende, and epidote, and the occasional presence of hypersthene, augite, monazite, kyanite and others points to direct derivation from pre-Cambrian crystalline rocks.

Investigation of the petrology of the various divisions of the Jurassic has proceeded rapidly during the past few years, the results being of surpassing interest. There is little doubt that the old "Armorica" supplied the material of the Lias and Inferior Oolite of the west of England, as it had done much of that of the New Red Sandstone, but with the passage of time the variety of rocks undergoing denudation was materially increased. We can thus account for the appearance of andalusite, pleonaste, chlorite, chloritoid, glaucophane, kyanite, monazite, sphene, and other minerals in this British area. As the deposits are followed north-eastwards some changes in petrography set in, although the distinctive minerals are those just mentioned, but when we reach the area of the Northampton Ironstone and the succeeding



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Bajocian, we might well expect the sediments to have come within the sphere of influence of the distributive provinces of Scotland and the now-buried Palaeozoic platform of the East of England. The evidence for and against a Scottish or Armorican provenance for the detrital minerals has been summarized by Mr. J. G. A. Skerl,[1] although the recent discovery of glaucophane in Scotland is a factor of some significance. The influence exercised, however, by the Palaeozoic rocks under the eastern and midland counties of England is entirely unknown. Little work has yet been done on the petrography of the Middle Jurassic rocks, but the mineral assemblage of the Upper Jurassic sediments of the Dorset area was shown by Dr. E. Neaverson[2] to be of Armorican origin, but that of the southern Midlands was ascribed to a northern source.

The more impoverished character and frequent small size of the minerals in the assemblages of the various Jurassic strata of Yorkshire is an argument against derivation of the Midland material from the Scottish area. The coarse-grained detritals of the Spilsby Sandstone are tentatively referred by Dr. F. T. Ingham[3] to a Scottish source, with the proviso that some may have been derived from ancient rocks nearer at hand, but now buried under younger deposits.

Thus we are brought to the consideration of the petrography and provenance of the Neocomian and Aptian rocks, one of the most interesting problems of British stratigraphy. Investigations are proceeding on the Wealden, the mineral constitution of much of which is of the impoverished type, and on the northern Neocomian deposits, which foreshadow, in their petrography, Lower Greensand conditions. Similarly, we have many scattered accounts and records of the petrography of the Lower Greensand (a term for the retention of which a plea may be made on the ground that it is useful as indicating a well-known transgressive sandy phase). These extend over the greater part of its outcrop, but no complete description has yet been published. The source of many of the curious boulders found in the Greensand has not been explained, and the same must be said of the detrital minerals. The relatively large size, freshness and abundance of kyanite, tourmaline, staurolite, and iron ores, and the presence (often locally in abundance) of sphene, hornblende, diopside, garnet, andalusite,

[1] *Proc. Geol. Assoc.*, vol. xxxviii, 1927, pp.

[2] The Petrography of the Upper Kimmeridge Clay, etc., *Proc. Geol. Assoc.*, vol. xxxvi, 1925, pp. 240-256.

[3] *Op. cit.* p.

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sillimanite, pleonaste, monazite, epidote, deep-red rutile, cassiterite, purple zircon and other minerals is suggestive of a source not far distant. Certainly we know of no pre-existing sediments from which these minerals could have been derived. The absence of other typical Armorican minerals even in the most westerly outcrops of the formation (such as the Isle of Wight, Purbeck and Wiltshire, makes a southern, as distinct from a purely western, source improbable. Moreover, the deposits die out westwards and are overlapped by the Albian, which contain abundant heavy minerals obviously derived from the western land-mass. Further, the Lower Greensand thins out northwards and becomes more impoverished rather than enriched in minerals in Yorkshire. A Scottish source thus seems improbable, even if such coarse grains of detrital minerals could have travelled so far and still remain relatively large and unabraded and unaltered in transit. The overstep of the Lower Greensand on to the Palaeozoic platform under the east and south-east of England therefore becomes of some significance. Is the platform anywhere composed of metamorphosed and crystalline rocks which could have yielded the minerals cited above? We do not know, and unfortunately, the Palaeozoic rocks reached by the various deep borings are on the whole not of the petrological type necessary. A gleam of hope is provided by such records as that of a boulder of tourmaline-granite supposedly from the Devonian in the Waterloo Bridge boring.[1] Although the Palaeozoic platform is but the continuation of the ancient mass forming the Crête du Condroz and Ardennes, we are not helped by the petrology of the Belgian Cretaceous and Tertiary deposits. The Wealden and Upper Cretaceous strata in Belgium contain a very impoverished mineral assemblage and it is not until Eocene times that kyanite, staurolite, and andalusite make their appearance. The difficulty of the problem is not lessened by the fact that kyanite and other typical minerals of the Lower Greensand have not been found in the Ardennes massif.

After Cretaceous times, there can be little doubt that Scottish influence on English Eocene, Oligocene and Pliocene sediments is difficult to trace. The material of these Tertiary rocks was probably obtained from sources much nearer at hand. It was not until glacial conditions supervened that the Scottish invasion of England was renewed.

[1] Fourmarier, P. Note sur la présence du granite dans le sous-sol de Londres. *Ann. Soc. Géol. Belg.*, 1927, vol. XLIX, B. pp. 317-319.

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It will be evident from the brief survey given above that the investigation of sediments bordering the Scottish Highlands (including the very interesting shore and glacial sands), and especially those of the area intervening between the Southern Uplands and Yorkshire and Lancashire must yield results of great interest. It would be of much value if some Scottish investigator would determine for us how far a particular heavy mineral like kyanite with a good cleavage, could travel from its source (either by direct transit or by relays), and what are the initial dimensions of grains and the relative reduction in size. Again, we may ask if such heavy minerals, which tend to settle and segregate, have travelled as far as or farther than the much larger but less dense pebbles, which like them, yield evidence of the source of sediments.

In the foregoing remarks, I have essayed to show the trend of recent investigations on the petrology of British sedimentary rocks. The attempt is likely to be regarded, and with justice, as in accord with the definition of an essay as 'a loose sally of the mind.' The results I have outlined have been summarized from the work of numerous investigators, detailed reference to which, for obvious reasons, was impossible in the limits of space here imposed. Included, also, are many unpublished records for which I must take responsibility.

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No. VI.—GENERAL GEOLOGY AND PHYSIOGRAPHY OF MORVERN, ARGYLL. By J. F. SCOTT, B.Sc., CARNEGIE RESEARCH FELLOW, GEOLOGY DEPARTMENT, THE UNIVERSITY, GLASGOW. Read 10th February, 1927; issued 7th January, 1928.

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## INTRODUCTION.

Morvern is situated in the N.W. corner of Argyll, and is included in Sheets 44, 52, and 53 of the one-inch map of Scotland. It

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forms a peninsula, extending south westwards between Loch Sunart and Loch Linnhe to the Sound of Mull, and is connected with the district of Ardgour by an isthmus about 7 miles wide. With a roughly triangular outline, it is bounded on the N.W. by Loch Sunart, on the N. by Loch Sunart and Glen Tarbert, on the S.E., by Loch Linnhe, and on the S.W. by the Sound of Mull.

The population is small and scattered, and the only village, Lochaline, has barely 100 inhabitants. Sheep are reared, but most of the ground is under deer. Cultivation is now almost entirely restricted to the raised beaches and to small patches on river alluvium. Lead was mined at Lurga in Gleann Dubh, but has not been worked since about the middle of the 18th century.

The name 'Morvern' is of Gaelic origin, and is derived from 'Mor-bhearna' meaning 'the great passes.' As is the case with so many Celtic place-names it is aptly descriptive of an outstanding feature of the area which bears it.

Of the early explorers of the district Macculloch shows the best understanding of the rock succession and distribution. He says little with regard to Morvern in particular, but his section from Gribon to Ben-y-attan indicates his clear appreciation of the relationship of the various important rock types.

Ami Boué, whose 'Essai Géologique sur l'Écosse' probably appeared within the next year (1820 ?), mentions the occurrence of granite near Strontian and on the western shore of Loch Linnhe. To the S. of Liegesdale (Liddesdale) he found rocks 'composées de feldspath brunâtre rouge compact et de quartz' which are no doubt the common quartz-felsites of that part. He also noted the increasing proportion of mica in the gneiss towards the lower end of Gleann Dubh. His section of Mull and Morvern is very similar to that of Macculloch.

James Nicol, in his 'Guide to the Geology of Scotland,' remarks on the 'secondary strata of sandstone and limestone' on Loch Aline, and on the trap which 'forms the summit of some of the hills in the interior, divided from the gneiss by the secondary strata with coal, this mineral appearing on the top of hills 2,000 feet high, resting on a metamorphic, and covered by an igneous rock.' Like that of Boué, his section (Fig. 28) is after Macculloch.

The work of Prof. Judd on the Secondary Rocks of Scotland is so well known that it needs no comment. With few exceptions he discovered all the known exposures of Mesozoic rocks on the

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West Coast. As regards Morvern in particular he found the Inninmore Carboniferous, and described in detail the Loch Aline Mesozoic sections and the famous outliers of Ben-y-Hattan (Beinn Iadain) and Ben-y-Hun (Beinn na h'Uamha).

In recent years those parts of Morvern which fall within Sheets 44 and 53 (Scotland) have been surveyed by the Officers of H.M. Geological Survey, and are described in the corresponding Memoirs.

## GEOLOGY.

### Summary.

1. The Pre-Palaeozoic foundation, intruded by
2. The Morvern (or Strontian) Granite, and covered in some places by
3. Sediments, varying in age from Carboniferous to Upper Cretaceous, these sediments having been preserved from denudation by
4. The Kainozoic Plateau Basalts.

The Pre-Palaeozoic foundation consists of Moine gneisses and schists, and comprises two very considerable areas, a central one and one in the north-eastern corner. The former area is roughly in the form of a triangle, extending along Loch Sunart shore for over 12 miles and narrowing southward till, on reaching the Sound of Mull shore, it is only found for a short distance on either side of Rudha an Ridire. The north-eastern area is comparatively small and stretches from Glen Tarbert along Loch Linnhe to Cilmalieu.

The Morvern Granite is one of the largest igneous bosses in Scotland, having a maximum extension from N.–S. of about 16 miles and from E.–W. of over 6 miles, and covering some 80 square miles. It is of two main types, a pink and a grey, the former being dominant along Loch Linnhe while the latter is found on the N. and W. of the outcrop.

From the point of view of areal extent, the sedimentary rocks are of little importance. They occur around the fringes of the Basalt Plateaux and form an easily weathered basement for these rocks.

The Kainozoic Plateau Basalts cover two principal areas, both bordering the Sound of Mull. One lies to the S.E. of Loch Aline, and the other from that loch westwards to Auliston Point. Small 'caps,' e.g. Beinn Iadain, occur to the N. of the larger of these plateaux.

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Pre-Palæozoic Foundation: Moine Series.

*Central Area.* The Moine rocks are of the following types:—

1. Psammitic (Rosenbusch's nomenclature), a metamorphosed impure arenaceous sediment.

This type has the greatest development of any of the Moine series. It is characterised by its very even banding which is indeed so regular that it seems to be determined by the original stratification. This conclusion is supported by the occurrence of false-bedding. In thin-section the rock, which is highly crystalline and shows few signs of decomposition, is seen to be composed almost entirely of quartz, felspar and biotite. A striking feature of many slices is the presence of a structure which closely resembles myrmekite.

The distribution of the psammitic gneiss is roughly as follows:—

*a.* A broad band from the Sound of Mull (Rudha an Ridire) to Loch Sunart (Laudale).

*b.* From Lochs Arienas and Teacuis northward to Loch Sunart.

*c.* Poll Luachrain to Druimbuidhe.

*d.* Shore W.N.W. of Sornagan.

Generally these gneisses are vertical or inclined at a high angle. Their strike of foliation is roughly N.-S. but there is much variation locally. In the southern part of the broad band (*a*) at Rudah an Ridire the strike is N.N.E., then N.N.W. from Loch Tearnait to the head of Glenn Dubh, and a N.–S. near Loch Sunart. In many places the direction of strike and the angle of dip of the foliation are much complicated by minor folds and fractures, *e.g.*, on the southern shore of Loch Teacuis, just E. of Torr an Eidhinn, the angle of inclination is less than 20°; in some places while only a few yards off it is almost vertical. A specimen from the eastern slopes of Beinn nam Beathrach resembles on the weathered surface a compact quartzose grit, the coarse clear quartz grains throwing into relief the small decomposed felspars. Another specimen is only distinguishable from the very pure psammitic type found in the north eastern area by the presence of small clear pink garnets.

2. Pelitic, a metamorphosed argillaceous sediment. This type is very rich in muscovite and biotite and has garnet as a common accessory. The banding in this rock is finer than in the psammitic and often the term 'schist' can be applied to it. It is

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generally fresh, but when crushed along a fault or dislocation, it soon crumbles away owing to the decomposition of its prominent constituent—biotite. When the rock is more thickly bedded than usual it frequently happens that hornblende and actinolite are developed along planes of movement. Small veins, sometimes 2–3 inches in thickness, are composed of these minerals, the former merging into the latter, which occupies the middle of the vein. Such veins are of course only noticeable where exposures are good, and are best seen on the shore of Loch Sunart E. of Rudha Aird Earnaich.

The pelitic gneiss is predominent in the following localities:—

*a*. Band from the head of Loch Aline (W. side) northward to Loch Sunart (Rudha Aird Earnaich).

*b*. Tom an Eildean band stretching N.E.–S.W.

*c*. Torr nan Con.

Garnet is particularly conspicuous in band *a*. near Loch Sunart (individual snowballs sometimes reaching 1½ inches in diameter), and in *b*. on the shore of Loch Teacuis S.W. of the island of Carna.

As regards its structure, it is very similar to type 1.

3. Semi-pelitic, a metamorphosed clayey sandstone or sandy clay. This type consists of alternating bands of types 1 and 2, and is characterised by the presence of frequent and often considerable lenticles of quartz and felspar.

It is most typically seen between Sornagan and Sgeir Bhuidh S. of Loch na Droma Buidhe.

In addition to these three types there are numerous occurrences of hornblende-biotite-schist. That these represent basic dykes is shown by their cutting the gneisses. Some well-exposed examples are found on the shore of Aird Beitheach, W. of Laudale.

Other foliated intrusions which have been classed by H.M. Geological Survey as lamprophyres are in a highly decomposed state, and, though common, are seldom well exposed unless in stream gorges and on the sea coast.

*North-eastern Area*. A small section of the Moine series exposed in this area falls within Sheet 52. The eastward continuation of these rocks has already been described by the Officers of H.M. Geological Survey and little need therefore be said regarding them. They consist of Psammitic gneiss of two types, one, as in the Central area, derived from an impure sandstone, and the other from a sandstone which must have contained a very

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small amount of impurities. Of these two types the latter predominates. As observed in the Memoir for Sheet 53, they are interfolded near the summit of Creach Bheinn. Both come into contact with the granite.

*Foliated intrusion of Dig an Aoinidh Mhoir.* A knoll lying to the S. of the stream flowing from Loch Doire nam Mart into Loch Arienas is composed of a small granite intrusion which exhibits 'lit-par-lit' injection of the surrounding psammitic gneiss. It is a fairly even-grained rock, consisting of quartz, buff-coloured felspar, and conspicuous biotite. It is seen, in hand specimen, to be distinctly foliated, and in thin section, the felspars are often bent without fracturing. Myrmekite is very well developed. The foliation of the granite is parallel to that of the gneiss, and is not so marked in the centre of the boss.

### Palæozoic: The Morvern Granite.

The Granite is of two kinds—a pink and a grey. The former occupies a broad belt along Loch Linnhe, while the latter is found on the N. and W. of the boss. It is probable that they belong to one intrusion as no contact has been found, and everywhere there is a gradual transition between them. Their difference in colour is due chiefly to the felspars which, in the pink rock, are salmon tinted, while in the grey rock they are light-cream to white. Though both rocks are typically porphyritic, the phenocrysts in the pink variety are very much smaller than those in the grey, in which they frequently exceed 1½ in., and give an appearance distinctly reminiscent of the Shap Granite. Further, there are two generations of phenocrysts in the grey rock—the first, larger, and more striking, being light cream potash felspars, and the second and smaller being grey lime-soda felspars. The felspar which gives 'body-colour' to the rock is of the latter type. In the grey rock also, hornblende and biotite are much more plentiful, and sphene is also a prominent accessory. With regard to the last mineral it is interesting to note that it decomposes very rapidly. In the fresh rock it occurs as beautifully clear brown diamond-shaped crystals reaching .2 in. in size, but on weathered surfaces it is quite opaque and has a dull clayey aspect. This feature was particularly observed in stream beds where the action of the organic acids from peat may have materially assisted the change.

The junction of the granite and the gneiss is essentially vertical

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along the whole of its extent. This feature is most noticeable where the slope of the ground is steep, *e.g.* from Loch Sunart southward. Generally it is well defined, but in some places (excluding those without Sheet 52) the margin is less definite owing to the number of granite veins in the gneiss, and also to the frequent occurrence of small bosses of basic diorite. Such bosses have been recorded in the Memoir for Sheet 53 as occurring on the Glen Tarbert or eastern margin of the granite, and it was found that they also occur on the western boundary especially near Liddesdale.

Inclusions of gneiss (accidental xenoliths) in the granite are much less common near Liddesdale than in the area near the Sound of Mull. Cognate xenoliths are found in abundance even at some distance from the granite margin and consist of basic clots which sometimes reach a considerable size (one in the Liddesdale Burn has a surface 6 ft. 6 in. by 5 ft.). A specimen collected near the Liddesdale road-fork shows the granite injecting a xenolith, the fine dark groundmass of which contains phenocrysts of potash and lime-soda felspars, hornblende and biotite.

A very interesting and complicated area lies to the N. and N.E. of Achleek, Loch Sunart. Approaching from the W., the normal hornblende-granite is found to be intruded by a basic diorite (dioritic appinite) similar to those found near the main margins. That it presents unusual features, however, is soon obvious as at a short distance from the contact, it becomes very coarse, and the usually dark green rock becomes still darker and almost black. The even grained diorite shows pink felspar subordinate to the ferro-magnesian minerals, while the coarse rock consists of large hornblendes and biotites together with quartz and alkali felspar. Except for the absence of olivine and serpentine (which were not observed) this rock is almost a typical scyelite. It is restricted to the Rudha na Srôine intrusion. This diorite near its western edge is cut by a vein of pegmatite consisting of pink felspar, quartz, and large plates of biotite.

Another diorite boss, occurring about 30 yards E. of the western boundary of the granite, is cut by numerous small veins of micro-pegmatite. A thin-section of one of these veins proved interesting. Its centre is pink while the edges are white, and along the junction with the diorite myrmekite structure is exceedingly well developed.

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South of Rudha Mhic Bheathiag (Loch Sunart) a vein of pink granite cuts the hornblende-biotite granite. Macroscopically it is distinct from the pink Morvern Granite in its freshness and lighter colour. Under the microscope, however, there is no great difference between the two. The felspars are zoned in the same way, the centre being sometimes oligoclase, sometimes andesine, while the outer zone is characteristically potash rich. This vein is over 3 miles from the nearest typical pink granite, and is the only known evidence to support the supposition that the pink and grey granites may be of slightly different age.

The Morvern Granite is considered by the Officers of H.M. Geological Survey to be of Lower O.R.S. age for two reasons, viz:—

1. "It is subsequent to the regional movements and metamorphism of the adjoining Highland schists and

2. It has close petrological affinities with the Beinn Nevis, Etive, and Southern Upland granites."

The only sediment found in connection with it is unfossiliferous, and occurs at Rudha na h'Earba on the W. shore of Loch Linnhe, N. of Loch a'Choire. It rests on granite and gneiss which form part of a block faulted down between the main Great Glen Fault and a branch fault lying to the W. It consists of red conglomerate and sandstone which show evidence of having been laid down under torrential conditions. The sandstone is in thin layers and alternates with the very coarse conglomerate. The fragments of the latter, which are rather angular, sometimes reach a size of one foot across, but the average is about 1 or 2 in. They are composed chiefly of the underlying granite and gneiss, together with pink pegmatite, red felsite, and vein-quartz pebbles, all well consolidated in a scanty matrix of red sand probably derived from the disintegration of the same rocks. The dip of the conglomerate is usually to the S. and S.W. at angles of 10°–20°, but at the southern end of the exposure the beds have an inclination to the N.W.

Although the constituents of the O.R.S. conglomerates vary locally according to their source and place of deposition, the conditions under which they were laid down appear to have been remarkably uniform. A striking similarity exists between the Rudha na h'Earba conglomerate and the various isolated patches of the formation found along the Great Glen, and particularly that lying to the S.E. of Loch Oich, opposite Invergarry, where the fragments are chiefly drawn from the local gneisses. The late

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Dr. Peach has suggested a Middle O.R.S. age for the Morvern outlier, this being founded on its resemblance to the basement members of the Orcadian O.R.S. of the Moray Firth Basin.

As regards the age of the Morvern Granite, therefore, it can be said that it is subsequent to the regional metamorphism of the Moine Series and Pre-Middle O.R.S. Both in its macroscopic and microscopic characters it is comparable to the Starav granite of the Etive complex which is regarded as being of Lower O.R.S. age.

*Other Igneous Rocks of Probable Lower O.R.S. Age.*

On the southern shore of Loch Sunart between Rudh' an t-Salainn and Rudh' an t-Sabhail, a very small boss of grey plutonic rock is exposed intruding the country gneiss. Though less than $\frac{1}{8}$ of a mile from the big granite mass, it is quite distinct from it in every way. It is almost non-porphyritic, and is finer grained and more compact. The bulk of the rock is composed of felspar, potash and lime-soda varieties being almost in equal proportions. The plagioclase is labradorite, and is therefore more basic than that in the Morvern Granite. Quartz is interstitial and much subordinate. Biotite is the principal accessory, and is disseminated very regularly throughout the rock. Hornblende is only seen in thin-section in very small idiomorphs.

Pegmatites which may be referable to the Morvern Granite are found intruding the gneisses for a considerable distance from the igneous rock. Though their texture varies, they are generally very coarse, so coarse indeed, that some of them have been quarried in the adjacent district of Sunart for mica and felspar. Similar but smaller veins occur on the southern side of Loch Sunart. One of the coarsest is exposed above the raised beach at Camas na h'Airbhe. It consists of pink and white felspar, quartz, muscovite and subordinate biotite. The felspar is dominantly potash rich. The muscovite only reaches a size of 3 in. in diameter by 4 in. thick, but makes up a considerable proportion of the rock. Where best exposed the vein has a trend 7° W. of N., but its course is irregular, being sometimes due N. and at others about 15° W. of N.

In the northern part of the area felsite dykes are numerous. They cut the granite, the diorite, and the gneiss, and vary in thickness from less than one foot to over 40 yards. In direction they trend approximately E.N.E., with local changes. They can

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be traced for a great distance, *e.g.*, from Allt a' Choire Dhuibh (W. of Loch Linnhe) to Eas Ruadh, E. of Beinn Iadain (over 9 miles).

In the upper reaches of Allt Leacach (Beinn nam Bheathrach), one dyke, the broadest in the district, has a width 125 ft., and a trend almost E.–W. Eastwards it divides into several smaller dykes, and six branches are found in the Liddesdale Burn. Its direction then becomes more northerly and in Allt na h'Airidh it is E.N.E.

These dykes are very uniform in character. The fresh rock is pink to buff, fine grained and compact. When weathered it often stands out conspicuously owing to its terra-cotta colour, and such a surface has an appearance like pisolite. Banding, in alternate light and dark shades of the colours above mentioned, is common, some specimens showing very thin bands, while others are much thicker. This feature is especially noticeable near the margins of the dykes, and is probably due to flow. In many cases these felsites are cut by basalt dykes which mostly trend N.W.–S.E. and are presumably of Kainozoic age.

The Eas Ruadh, which is quite a big stream, derives its name (The Red Water) from the fact that its bed is almost covered with red boulders taken from the several felsite outcrops through which it cuts its way. Near the source of this burn, also, one of these dykes has been involved in an E.-W. fracture zone. It was crushed and brecciated and then recemented by silica and calcite into a very hard rock.

A common feature of thin sections of these felsites is the presence of corroded phenocrysts of quartz.

Several small dykes of lamprophyre cut the gneiss. Two occur N. of Barr, on the raised beach W. of the river. The more important is fairly fresh, and has a N.E. trend. Dykes of similar composition and orientation occurring in Mull and Lismore are considered by the Officers of H.M. Geological Survey to be of Lower O.R.S. age.

Many N. and N.W. dykes of supposed Kainozoic age follow the line of previously injected dykes. The latter are usually in a high state of decomposition, being reduced to a yellowish-green clay. Instances of this occur in Allt na Mine and Creag Dubh,

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and others are found in association with the metalliferous veins of Bellsgrove, Strontian.

*Carboniferous.*

The Carboniferous Strata of the Inninmore of Ardtornish were discovered by Prof. Judd in 1877, and have since been described in detail by the Officers of H.M. Geological Survey.

A further exposure of beds of this age, occurring on the western shore of Ardtornish Point, W.N.W. of Ardtornish House, was encountered by the present writer in 1924. These beds appear to correspond with the lowest of the Inninmore section, as they consist of sandstones very similar to those exposed below high-water mark at the head of Inninmore Bay. Lower Lias (Gryphaea) Limestones rest unconformably on gritty, dark green and grey micaceous sandstones, the uppermost of which (the gritty) contains remains of Calamites, while all show traces of carbonaceous material. The gritty and dark green bands are false-bedded. The outcrop is in the form of a ridge running E.-W. It passes under the Lias limestone landward and on both sides, and under the sea westward. The exposure is only visible at low water during spring-tides, when the total thickness seen is less than 5 ft. The Gryphaea limestone is only 9 ft. thick, and is succeeded above by a roughly columnar lava.

MESOZOIC: *General Description of West Coast Sediments.*

Of the Mesozoic rocks of the West Coast, the Trias covers the greatest area and is found in patches from Rudha Dunan (E. of Summer Isles) in the N. to Loch Spelve (Mull) in the S. Though its thickness varies from place to place, and often within very short distances, its general characteristics remain remarkably uniform over the whole area. The most typical basal bed consists of a conglomerate or breccia chiefly composed of the underlying formation which is Torridonian in the N. and Moine in the S. Cornstone is likewise common and bears a somewhat peculiar relationship to the rocks upon which it rests.

The passage from the Trias to the Lower Lias is usually insensible. Sometimes the beds are arenaceous and resemble the Trias, while others might be placed with the Broadford Limestones. The only locality where these passage beds are definitely referred to the Rhaetic is at Allt na Teangaidh, S. of Gribun in Mull.

The Broadford Beds have a wide distribution and the presence of

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the Gryphaea Limestone is common to most of the exposures from Loch Ewe to Mull.

These limestones and thin shales are succeeded by sandy shales—the Pabba Series of Prof. Judd—which have practically the same distribution as the Broadford Beds, but are usually much better developed. Their maximum thickness is 600 ft. in Raasay, over twice that of the underlying limestones.

In Morvern, the Pabba shales are followed by Cenomanian greensand which rests on them with marked unconformity and overlap. The upper Cretaceous strata, though thin, are very persistent. Their unconformable relations with the older rocks is everywhere noticeable. In Strathaird the basal bed is a coarse grit or fine conglomerate which contains pebbles largely drawn from the underlying Oxfordian sandstone. The total absence from every part of the area of any sediments of Lower Cretaceous age, together with the presence of such conglomerates, points to the passage of a very considerable interval of time between the deposition even of the Corallian and the deposition of the Upper Cretaceous. If Lower Cretaceous strata were deposited, then subsequent erosion must have been correspondingly greater than if they had not been deposited.

The preservation of the Mesozoic rocks of the West Coast is due to two main agencies—the protective covering afforded by the Kainozoic basalts and faulting. The only Mesozoics preserved without the aid of these agencies are the isolated patches at Tarscavaig, Rudha Dunan, etc., where denudation has probably succeeded in removing the whole series with the exception of the Trias, which, being the oldest and therefore the most protected, had the best chance of escaping the ravages of time.

### *Trias.*

Of the Mesozoic rocks of Morvern the Trias has the greatest areal extent. Its maximum thickness of 300 ft. is found in the Inninmore of Ardtornish. This occurrence is also exposed on the northern slopes of the Glais Bheinn (An Dunan) Plateau where its thickness is less than 70 ft. This variation takes place within a distance of 1¼ miles.

The best sections occurring within Sheet 52 are exposed in the small streams at Larachbeg.

The following table gives the succession:—

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| | |
|---|---|
| Greenish calcareous sandstone .. .. .. .. .. | 10 ft. |
| False bedded greenish-white sandstone with many water-worn Pebbles .. .. .. .. .. .. .. | 15 ,, |
| Coarse red calcareous grit with Conglomerate at base .. .. | 60-70 ,, |
| Moine (pelitic). | |

The basal conglomerate (or breccia, in some places) is well exposed in a little waterfall immediately W. of the iron bridge over the Aline. It is similar to that found in Coire Slabhaig (northern outcrop of Inninmore Trias), the only difference being that there the foundation is psammitic Moine whereas at Larachbeg it is pelitic Moine. Owing to the greater richness of the pelitic gneiss in the micas, particularly biotite, the rocks derived from it are much redder in colour than those which rest on the psammitic type. Thus the Larachbeg conglomerate has a very red matrix, while that of Coire Slabhaig is much lighter. The thickness of the conglomerate also varies from a few feet at the former locality to over 40 ft. at the latter. The fragments of gneiss contained in this bed are sometimes over 2 ft. in length, and though they predominate, vein quartz is also an important constituent. The basal conglomerate merges upward into the coarse red grit which is exposed in the same waterfall and also in another about 15 yards further N. Most of the thickness of the grit is obscured by a terrace of sand and gravel at about 100 ft. above sea level. Just S. of the houses and above the road, it passes first into a soft brownish-grey sand, and then into a greenish white sand which is false bedded and contains lenticles of conglomerate showing water-worn fragments of gneiss, quartzite, and vein quartz. Towards the top of the series the sediment becomes very friable and richer in calcareous elements. To the S. of this section the junction with the Moine is exposed in seven localities, six of these being in the plantation between Larachbeg and the Allt na Croite and the seventh in that burn immediately N. of Kinlochaline House. In three of the six outcrops cornstone is seen in conjunction with the gneiss. Southward there is no further exposure of the actual junction, and at the N.W. fault which is partly shown in Sheet 44, it must fall below sea level. Northward, the base can be traced easily, as the contact is seen in most of the streams. The outcrop swings to the N. and W. in a line roughly parallel to the basalt scarp, until it is cut off by a fault running slightly W. of N. With the exception of two exposures, one W. of Kinlochaline House and the other at the Torran nam Broc, the



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upper part of the series is quite obscured either by talus from the basalt or by landslip material (as at Coire Achadh nan Gamhna). At Kinlochaline House the basal breccia is succeeded by a red marly grit which passes into sandstone with cornstone. The last is well seen where the path crosses the burn. The red grit is exposed at the Torran nam Broc. The faults which bound the outcrop above described are taken to be continuous, not only with each other, but also, in a S.E. direction, with the one which cuts the cliffs on the opposite shore of Loch Aline and swings to the S. till it reaches Ardtornish Bay; and again, in a northerly direction, with the series of faults which affect the outlier of Beinn Iadain.

Westward from the Allt a' Choire fault (the one above mentioned, running W. of N.) which has a vertical displacement of some 250 ft. and a horizontal displacement of nearly ½ mile, Triassic rocks outcrop on the shore of Loch Arienas, S. of Rudha an Aoinidh Bhig. Here again everything but the basal contact of the series is obscured. The rocks of this exposure are somewhat similar to those occurring at Rudha an t'Sasunnaich (E. of Ardtornish House). They consist chiefly of cornstone with layers of chert. In some instances a pale creamy limestone predominates, and in this the banded chert appears to line cavities and be in turn coated with, and its hollows sometimes filled by, small calcite crystals. Reddish gritty bands alternate with the more calcareous layers. These beds are only exposed for a short distance from the loch-side, but their western continuation for at least ½ mile is shown by the contour of the ground.

Between this outcrop and the corrie below Sithean na Raplaich there are no exposures of the sedimentaries, chiefly owing to the vast accumulation of talus and land-slip material. In any case they must be very thin as the gneiss approaches close to the steep talus slope.

In Allt an Aoinidh Mhoir, about ½ mile W. of the ruins, and also in the second tributary to the S.W., the junction between the Trias and the Moine is again exposed. In the latter and better of the two localities, red grits are seen resting almost horizontally on steeply inclined psammitic Moine. About 200 yards up this burn and near its junction with another, a band of highly calcareous grit is exposed. It weathers dirty yellow and white in patches, and contains abundant cornstone concretions. Fairly well-rounded

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pebbles of vein-quartz are also common. In Allt an Aoinidh Mhoir cornstone forms the basal bed, and its intimate association with the gneissic floor is striking. This exposure is interesting in that along the 100 yards of outcrop with a gradient of 1 : 5 to 1 : 7, it is the junction with the gneiss which is exposed over the whole distance—illustrating the transgressive nature of the series.

The outcrop of the Trias on the S. side of Loch Teacuis consists almost entirely of the junction with the underlying gneiss. To the W. of Rudha nan Laoigh the association of cornstone and gneiss is very well exposed just above h.w.m. In this instance, as in the several already mentioned, there is the same curiously intimate relationship between the Moine foundation and the overlying cornstone. The cornstone is seen filling in even the minutest cracks in the gneiss and permeating for a very considerable distance along its foliation planes. Its constitution is apparently only slightly affected by its immediate surroundings; on the pelitic Moine in the plantation S.E. of Larachbeg it is seen, on a fractured surface, to be even whiter and is richer in lime than that on the psammitic gneiss, either in Allt an Aoinidh Mhoir or on the S. side of Loch Teacuis. At the locality S.E. of Larachbeg, the weathered cornstone is coated with a light-green deposit which gives it the appearance of being covered with fine fresh-water algae. This coat is less calcareous than the white cornstone proper. In Allt an Aoinidh Mhoir the rock is yellowish-white in colour, and in many places all that is left of it is what occurs between the weathered edges and along the foliation planes of the gneiss. Small roughly vertical veins of a much purer limestone traverse both the cornstone and the gneiss. That is, some of them run parallel to the foliation planes of the gneiss, but others are seen to be continuous through the ridges between these planes where no cornstone is present—only the vein itself. The cornstone contains only a few scattered sand grains—is merely dusted with them.

At Loch Teacuis the best exposure of the junction happens to be on top of a zone of crushing in the gneiss. Here the cornstone penetrates the fractured rock for even a greater distance than usual and is greenish and micaceous owing to the inclusion of a fair amount of muscovite. A few inches above the actual ridges of the gneiss the cornstone usually becomes faintly bedded, and this feature develops as the thickness increases.

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Near this cornstone (on Loch Teacuis side), and presumably above, follows a calcareous conglomerate, the fragments of which consist of vein-quartz chiefly, but granitic and gneiss pebbles are also present—all imbedded in a cornstone matrix. The granite is of no local type, being a very pale pink non-porphyritic variety cut by quartz veins, and the gneiss might come from any Moine locality.

The most feasible conclusion to be drawn from the examination of the cornstone is that it originated by deposition from solution in waters, which, owing to an arid climate with scanty wet seasons, were drawn towards, and evaporated on, the surface during the long dry seasons. The limestone veins are regarded as the channels through which the upper layers of cornstone received their calcareous material. The sandy elements, at least near the base are certainly derived by disintegration from the subjacent gneiss. For the higher parts of the series—the sands with associated conglomerates—it is necessary to stipulate the work of running water—at least during certain periods—which again suggests a distinct seasonal distribution of the rainfall. Their colours likewise are reminiscent of deposits laid down under semi-arid tropical conditions.

*Beinn na h'Uamha.* Cornstones and grits are sometimes exposed on the N.E. face. They do not occur on the southern side as there Cretaceous rocks rest directly on psammitic Moine.

*Beinn Iadain.* Marly sandstone with cornstone and occasional grits are seen at intervals (with the exception of the E. side) round the "basalt cap." As is almost always the case with these marginal deposits, what is exposed at one time may be completely obscured for a long period by a sudden landslip. This was found to be particularly the case on the northern slope of Beinn Iadain. During the short period of one month, three known outcrops were obliterated while one fresh one was exposed.

*Beinn Ithearlan.* Cornstone is exposed on the E. and N.E. margin of the "basalt cap."

*Beinn Ghormaig.* A suggestion of Trias red grit is found on the S.E. side. The soil at one point has the appearance of being derived from such a deposit.

### *Passage Beds.*

Strata which may be of Rheatic age, occur on the eastern shore of Loch Aline, and have already been described in the Memoir

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for Sheet 44. They show affinities to the Trias in that they are distinctly sandy—at least as far as can be seen. There is a gap of some 20 ft. below the Lower Lias limestone, and this part might show a transition.

At Larachbeg, a thin band of exceedingly fine black shale intervenes between the Trias sand and the Broadford Beds. The appearance of this occurrence suggests a small lake of very limited extent resting in a hollow in the Trias, the top of which is slightly iron-stained. There is a sudden break in the type of deposition at the top of the shale, but not an obvious unconformity. The shale is crowded with plant remains, and certain thin bands contain small fresh-water lamellibranchs. In external appearance the plant remains resemble leafy liverworts, but when one of the "leaves" is examined under the microscope the most striking feature is the presence of stomata. Other structures are reminiscent of certain conifers. The description of this shale and its organic contents is held over until the detailed examination is completed.

### *Jurassic.*

The Lower Lias is the only part of the Jurassic system which is represented in Morvern, and of that small section the Broadford limestones are the only members which actually outcrop in the area within Sheet 52. The Pabba shales are present but are almost always obscured, partly by talus, but mostly by the soft water-logged clay resulting from their own decomposition. They give rise to a type of slope which, in Morvern, is peculiar to themselves; when encountered in the correct position relative to the Broadford Beds and to the Greensand, this slope is diagnostic of their presence. Though steep, it is always saturated with water and yields a 'mushy' surface which often extends over a large portion of the underlying limestone. Only in the localities on both sides of Loch Aline and in the Inninmore of Ardtornish are the Pabba Shales exposed.

The Broadford Beds, consisting largely of hard limestones with shaley partings, are seen at the following points in Sheet 52.

1. Larachbeg Burn (about 2 ft. exposed), and at very rare intervals W. of Coire Achadh nan Gamhna to the Allt a' Choire Fault.

2a. S.E. Rudha nan Laoigh, in continuation with

2b. W. side of Ard an Tiobairt, below the bridle-path and beyond the park wall.

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3. Rahoy Burn, in a small faulted block.
4. Beinn Iadain, S.E. face.

At locality 2b. (the only good one) about 20 ft. of strata are exposed and these represent the upper portion of the Gryphaea Limestones. The following fossils, in a fair state of preservation were obtained:—

*Gryphaea arcuata*, Lam. the characteristic fossil sometimes almost reaching 4 in.
*Lima* (*Plagiostoma*) *gigantea* (Sow.); one specimen reaches 5 in. by 6 in.
*L. pectinoides* (Sow).
Pentacrinine columnals, very abundant—almost a crinoidal limestone in places.
*Pecten* sp.
? *Pinna* sp. cast.
Ammonites are rare and badly preserved.

The limestone was quarried at this place for burning. The relation to the beds both above and below is obscured.

The section is probably bounded on the W. by a N.E.-S.W. fault. There is no actual exposure along its line, but the fact that the sedimentaries are found to the E., and the gneiss to the W. of a small burn and at the same level, cannot be otherwise explained.

In Rahoy Burn (locality 3) there is a small outcrop of the same limestone, which no doubt also supplied stone for burning as there is a kiln about ½ mile to the S.E. along the loch-side.

On the S. face of Beinn Iadain above the Lon Mor, a few feet of the Gryphaea limestones are exposed, and the top of the series is marked by the presence of a line of springs. The only source of this water is the catchment area on the summit of the hill, where it collects in a small loch or tarn which must have a fair depth as the springs continue with unabated strength during even the driest summer. The specimens of Gryphaea from this locality are not so large as those obtained at Ard an Tiobairt. *Lima pectinoides*, and fragments of *L.* (*Plagiostoma*) *gigantea* are also present, together with a few casts of ? *Modiola* sp.

### *Upper Cretaceous.*

The distribution of the Upper Cretaceous strata on the West Coast serves to illustrate the great Cenomanian Transgression emphasized by Suess in his 'Enstehung der Alpen.' The variety of foundations upon which these rocks rest is very striking and

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nowhere is it more noticeable than in the district under consideration.

In Morvern the general succession is as follows:—

Silicified chalk (Beinn Iadain).
White desert sandstone (largely unfossiliferous).
Greensand with *Exogyra*.
Greensand, unfossiliferous.

In the area within Sheet 44 the whole series, with the exception of the silicified chalk, is well exposed on both sides of Loch Aline and in the Inninmore of Ardtornish. In these sections the basement consists of Pabba Shales.

The unfossiliferous greensand is intensely glauconitic, and very deep green. It is thin-bedded, the various layers being sometimes less than $\frac{3}{16}$ in. in thickness. Rare patches with a more siliceous matrix stand out like concretions. The grains are somewhat small and angular, and are imbedded in a calcareous matrix through which the glauconitic grains are disseminated. This band is from 2–3 ft. thick, and is succeeded by a much thicker bedded, more calcareous, less glauconitic, and highly fossiliferous greensand. As the distance from the basal bed increases, the glauconitic content becomes less, and the colour becomes lighter green, and then grey. The typical fossil is *Exogyra conica*, Sow., and often the beds are so crowded with them, that the rock is really a sandy limestone. The total thickness of the greensand varies around 30 ft.

White sandstone overlies these beds, and forms one of the prominent features of many cliffs. It is about 40 ft. thick (maximum), and is wonderfully pure. Only along joint planes, where water percolates from the basalt above, does staining occur, and then for no appreciable distance. Only in one place in Morvern, Beinn Iadain, is the series concluded by silicified chalk 3 ft. thick.

Upper Cretaceous rocks are exposed in the following localities within Sheet 52:—

1. W. of Kinlochaline to the Allt a' Choire Fault.
2. Allt a' Choire, 150 yards above the bridge and on the slopes of Sithean an Aoinidh Bhig.
3. S. side of Loch Teacuis, above Lower Lias on both sides of the bridle-path.
4. Immediately W. of Allt Garbh (W. of No. 3).
5. S. face of Beinn Iadain.

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6. Beinn Ghormaig.
7. Beinn na h' Uamha.

Between Kinlochaline and Achadh nan Gamhna, the series is fairly well exposed, particularly the upper parts of the greensand and the white sandstone. The latter is always a noticeable feature as there is a marked contrast between it and the overlying black basalt. The thin-bedded greensand is exposed in a few burns W. of Coire Achadh nan Gamhna. In the Allt a' Choire, in the W. side of the fault, the white sandstone again outcrops. To the N. of Sithean an Aoinidh Bhig it is prominent in the cliff. Between it and the loch-side everything is obscured by a landslip which brings great masses of lava right down to the loch. The fossiliferous greensand was only seen once after a flood in the Allt at Choire, in a position not far distant from the white sandstone. Fragments of the thin-bedded variety are found along the western slopes of Sithean an Aoinidh Bhig. In this section the only sign of Lower Lias rocks is the occurrence of a few pieces of Gryphaea limestone and the presence of a line of springs, the most northerly of which is at the road-side and is called ' Tobar na Coimhlinge.'

The exposures on the S. side of Loch Teacuis are, with the exception of Beinn Iadain, the best within Sheet 52. The unfossiliferous greensand is not seen, but the upper calcareous part is well exposed and yielded some fairly well-preserved fossils. *Exogyra conica* is very plentiful, almost to the exclusion of other fossils. A fine *Pecten orbicularis*, Sow. was found and also an impression of *P. cf. asper*, Lam. *P. quinquecostatus*, Sow. was seen only at the Loch Aline sections. Worm tubes are common. Landslips have obscured part of the section, and in one place the Exogyra greensand is found at the waters edge. The white sandstone is the most persistent member of the series and outcrops on both sides of the bridle-path. Westward, near Allt Garbh it is again seen for a short distance, resting on gneiss and overlain by basalt.

On the right bank of the Barr River and in line with the southern wall of the park, it forms a small cliff. The rock is slightly coarser than usual and, owing to the marshy ground above, is somewhat iron-stained. Traces of it are found at a spring just E. of this exposure, and on the left bank it is seen mounting the slope for about 150 yards. Westward from this point there are no further exposures.

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On Beinn na h'Uamha the sandstone outcrop is duplicated by an approximately N.–S. fault. The western end of the basalt cap has been let down for nearly 400 ft., and the sandstone is exposed to the E. of, and above the line of fault. The sandstone cliffs at the N.W. corner of the hill, and their higher counterpart at the fault, can be seen for a considerable distance. On the southern face the sandstone rests on gneiss, but on the N. side Trias forms the foundation.

The most complete exposure on Beinn Iadain occurs at the eastern end of the southern face. The outcrop lies immediately to the N. of a ruined shieling, and is bounded on the E. by a N.–S. fault. The line of this fault is obvious in the gneisses themselves, as there is quite a distinct ridge running down the eastern edge of the Lon Mor Beinn Iadain. Two small parallel faults lie to the W. of the main one, and affect the Mesozoic outcrops. The basal beds of the greensand are, as in the other localities, highly glauconitic, but the rock is in lenticles of alternate green and greyish-yellow colour. It also contains a number of small cherty concretions, and does not break as readily as usual along the bedding planes. This is succeeded by the usual Exogyra greensand which becomes increasingly rich in calcareous elements towards the top. The white sandstone follows, but is not so wel l exposed as on Beinn na h'Uamha. The silicified chalk is a most compact rock, but in some places the silicification has not proceeded very far as the chalk comes off on the fingers when the stone is touched. Some small fragments of Belemnite guards [which may belong to *Belemnitella mucronata* (Schloth.)], together with plentiful *Inoceramus* prisms were found. In thin-section the rock is seen to be crowded with Foraminiferal remains, among which were many specimens of *Globigerina*, along with Rotalian and Textularian forms. The crushed rock yielded better results, and some, *e.g.* *Testularia globifera*, Reuss., *Calcarina*, were determinable.

This isolated fragment of the Chalk resembles the Antrim development much more closely than it does those to the N., *e.g.* those in Eigg or Skye. In Eigg the chalk occurs in patches in sandstone. In Skye, at Soay Sound, it is much more of a chert, while in Strathaird it bears the closest likeness to the Morvern rock. In the last locality it is metamorphosed to a slight extent and contains harder areas which are just a little darker and have a more even fracture than the Beinn Iadain Chalk.

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On Beinn Ghormaig Upper Cretaceous rocks are represented by a small outcrop of the white sandstone. It occurs a few yards E. of the track where it crosses the fault bounding the W. side of the basalt cap. The greensand is not exposed but is probably also present as small fragments of the fossiliferous portion are found in the talus.

*Kainozoic: Sediments.*

Sediments of this age are chiefly restricted to mudstone-with-lignite underlying the lavas. It is only a few feet in thickness and is sometimes, though very seldom, absent. It has no abnormal features except that it contains carbonaceous matter which, in places, is of sufficient quantity to give an inferior lignite. It is purplish-brown and red in colour, and breaks into such small fragments that it is almost impossible to secure a good specimen. Its general appearance, as noted in the Memoir for Sheet 44, suggests the lateritic weathering of a basaltic ash.

On Beinn Iadain, below the lignite, patches of sediment occur, consisting of a rather dirty white calcareous sandstone which, like the overlying bed, contains carbonaceous remains. Somewhat angular fragments of the silicified chalk are also included. Although this is poorly exposed, being seen only at one place, when it is taken into consideration along with the phenomena of the careous-weathered chalk of Gribun and its associated sediment it certainly is valuable support for the supposition that the Cretaceous rocks were upraised and suffered the atmospheric weathering of a desert climate—leading to the silicification of the upper portion—before the outpouring of the lavas.

*Lavas.*

All the lavas of Morvern are without the pneumatolysis limit of the Mull Centres. Little description is necessary as the area which falls within Sheet 44 has been described in the corresponding Memoir, and is typical of the whole development in Morvern.

Their main features are trap-featuring, rusty spheroidal weathering, and massive centres becoming amygdaloidal towards top and bottom (the band at the top being thicker, with purple and red staining). In the same Memoir (p. 105) the thinning out of the lava-flows northward is mentioned. The same conclusion was reached during the present investigation, and, in addition, the following point was noted. Seen from Tobermory, the Morvern lavas have an appearance suggestive of the interdigitation

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of lavas from the N. and lavas from the S., *i.e.* from Ardnamurchan on the one hand and Mull on the other. As is usually the case, the lavas are non-porphyritic, but some exceptions were observed; *e.g.* a flow near the base of the sequence above the house at Ard an Tiobairt, shows porphyritic felspars, another, likewise near the base, occurring in the Barr River.

The maximum thickness of the lavas as seen in the precipitous slope E. of Sithean na Raplaich is about 1200 ft. The basalt caps of Beinn na h'Uamha, Beinn Iadain, and Beinn Ghormaig attain respective thicknesses of 200-250, 650-750, 150-200 ft.

*Dykes.*

The majority of the dykes in Morvern show the trend characteristic of the Mull swarm, N.W.–S.E., but some have directions varying between N. and W. to S. and E. By far the commonest trend however, is between 40° W. of N. and 40° N. of W. They are exceedingly abundant and often form prominent features of the landscape. As they are of the same types as those found in Mull—plateau basalt and porphyritic central lava—little need be said regarding their petrology. In the northern part of the area, E. of Lochan Dhonnachaidh, only a few dykes exceed 5 ft. in thickness while the average is less than 2 ft. W. of that point much larger examples are frequent, *e.g.* a dyke a few yards W. of the loch is 30 ft. wide and one near the mouth of Glencripesdale is nearly 100 ft.

Some interesting individual dykes were encountered. A small dyke, occurring about ½ mile N.E. of Clonlaid (Gleann Geal) and cutting the gneiss parallel to its foliation, was found to show corroded felspar phenocrysts which include spheroidal areas of dark glass with microlites. The dyke rock is a tholeiite of Brunton Type. Near the western boundary of the granite, at a point ½ mile W. of the 'Lochaline 10' milestone, there are two N.W.–S.E. dykes in association, both cutting granite. The broader and more southerly is 5 ft. wide, while the other, which is separated from it by 4 ft. of granite, is only 2 ft. 6 in. in thickness. The former is of normal plateau type, but the latter is seen to be out of the ordinary even by its weathering. Its surface is made irregular by the presence of harder patches which stand out prominently and at once draw attention. These patches were found to be composed of accidental xenoliths of gneiss and granite. The dyke at this exposure is seen cutting an area where gneissic

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inclusions are common in the granite. In thin-section the inclusions (in the dyke) are seen to have taken on an entirely new appearance, owing to having been recrystallized. They consist of a mosaic of quartz and felspar (Or. and Plag.), and most of the crystals show a roughly hexagonal outline. The normal dyke-rock is again a tholeiite, but is distinct from the last example in having acicular augite and being much richer in magnetite.

Jointing of dykes is a common feature, and is usually parallel to the margins, but is sometimes in rough horizontal columns, *e.g* one at Na Caistealan, Beinn Iadain, and another on the S. side of Loch Sunart at Rudh' an Torr-mholaich.

## Glacial and Recent.

From the accompanying map it will be seen that during the Ice-Sheet Glaciation the direction of flow in the northern part of the area was approximately N.E.–S.W. In the southern part the flow was in a more westerly direction, owing to the dividing and diverging of the ice-sheet on either side of the Mull nunataks. An important point to notice is that the ice was little affected by two of the chief valleys—Loch Sunart and the Arienas-Teacuis valley—crossing both almost at right angles.

Erratics are common all over the area. On the granite in the N. there are numerous boulders of gneiss from the Ardgour district. The most plentiful erratic is the granite itself, and large blocks of it are found scattered all over the ground to the S.W. of its outcrop. Sedimentaries are much rarer and are principally represented by Trias sandstone (*e.g.* S.W. of Barr, at an altitude of 1120 ft.).

Boulders of red quartz-felsite are also found, *e.g.* near the summit of Beinn Iadain, and fragments of coarse pegmatite, similar to the veins exposed near the granite are sometimes encountered on the hill-slopes to the S. of Loch Sunart.

Roches moutonnées are of frequent occurrence. One of the best and most accessible is just S. of Claggan School-house. It has the ' stoss ' side facing W. of S. There are many examples on Meall Achadh a' Chuirn (N. of Acharn), while on the N. side of that hill and S. of the Lochanan Dubha, are some fine instances of perched blocks of granite resting on gneiss.

Gleann Dubh is the only instance of an important glen trending parallel to the path of the ice-sheet. Being so, it shows every sign of having been thoroughly glaciated. In the other valleys

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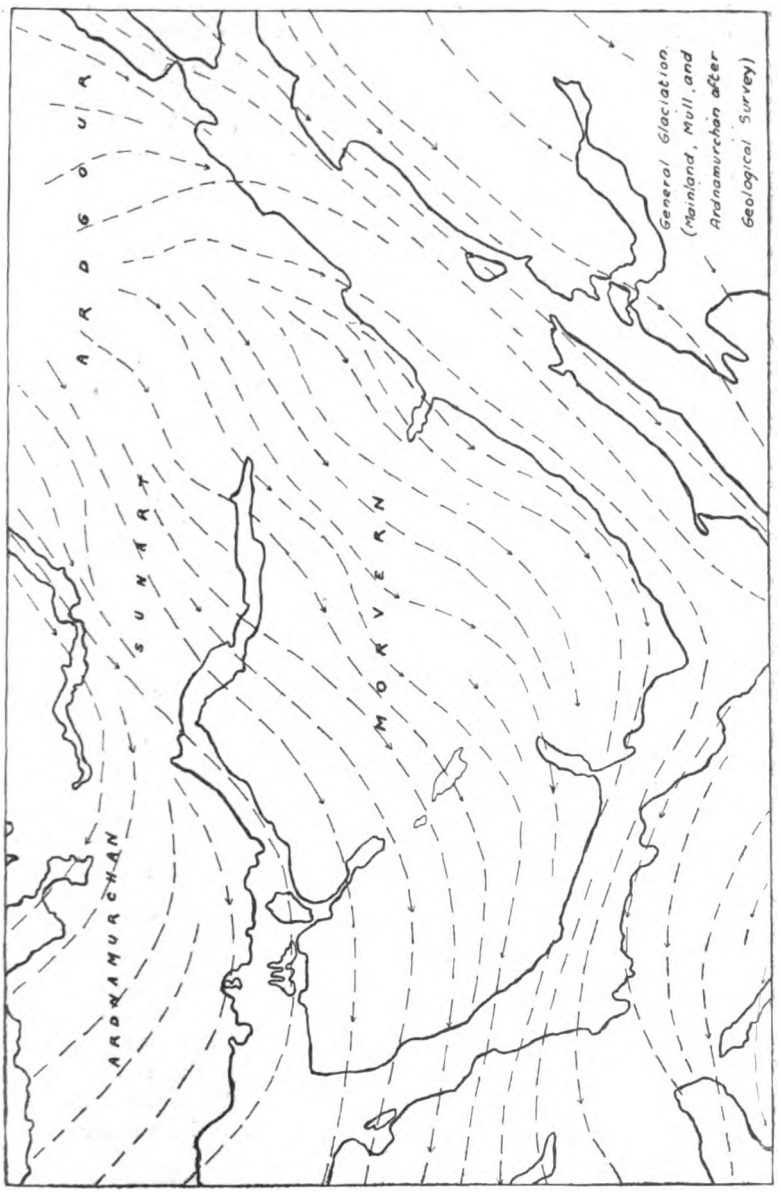


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there are many signs of local glaciation, which is taken as being in relation to the valleys themselves, *e.g.* on the shores of Loch Teacuis a set of striae run in a N.W. direction; Glen Tarbert, Glen Laudale, Glen Galmadale, etc., also show signs of valley glaciation, and small corrie glaciers were present in the glens S.W. of the head of Loch a' Choire, N.E. of Sithean na Raplaich, etc.

Raised Beaches occur at three different levels, about 100, 65 and 25 ft. above sea level. Of these the last is definitely post-valley-glaciation as in at least two places it is seen cutting into terminal moraines (Glen Laudale and Glen Galmadale). The two older beaches are not preserved to any extent on the sea coast but remnants are found along the Arienas-Teacuis valley, the Aline valley, and Lower Gleann Geal. The intermediate one is only developed definitely N. of Acharn, and its surface is strewn with great granite erratics which are roughly disposed in a fan-like arrangement originating at the point where the Black Water enters the open valley. It is not seen in contact with the 100 ft. beach, as the channel of an old course of the Black Water lies between the two.

## Tectonics.

The major faults of Morvern follow well-defined directions *viz*:—N.–S., approximately E.–W., and N.E.–S.W., the first two of these being roughly diagonal to the last. The N.E.–S.W. trend is principally shown by Loch Linnhe, Loch Sheil and Loch Sunart, and is of Caledonian age. The injection of the Mull centres, giving rise to a resistant block, and followed by the subsidence of that area, no doubt caused the diagonal faults in the country lying immediately to the N. and between the two old Devonian shatter-belts. The N.-S. faults are the more important of the two diagonal sets. The well known Inninmore Fault is an example. It was thought by some past writers, *e.g.* Judd and Geikie, to swing to the N.W. in the northern part of its course. The former said that it limited the outlier of Beinn Iadain on the E., and the latter held it at least partly responsible for the great valley containing Lochs Arienas, Doire nam Mart, and Teacuis. No field-evidence to support such a change of direction was found. On the contrary the fault may be traced for about 7 miles almost directly northward, and it apparently fades away (at least it no longer remains a noticeable feature) just S. of Gleann Dubh.

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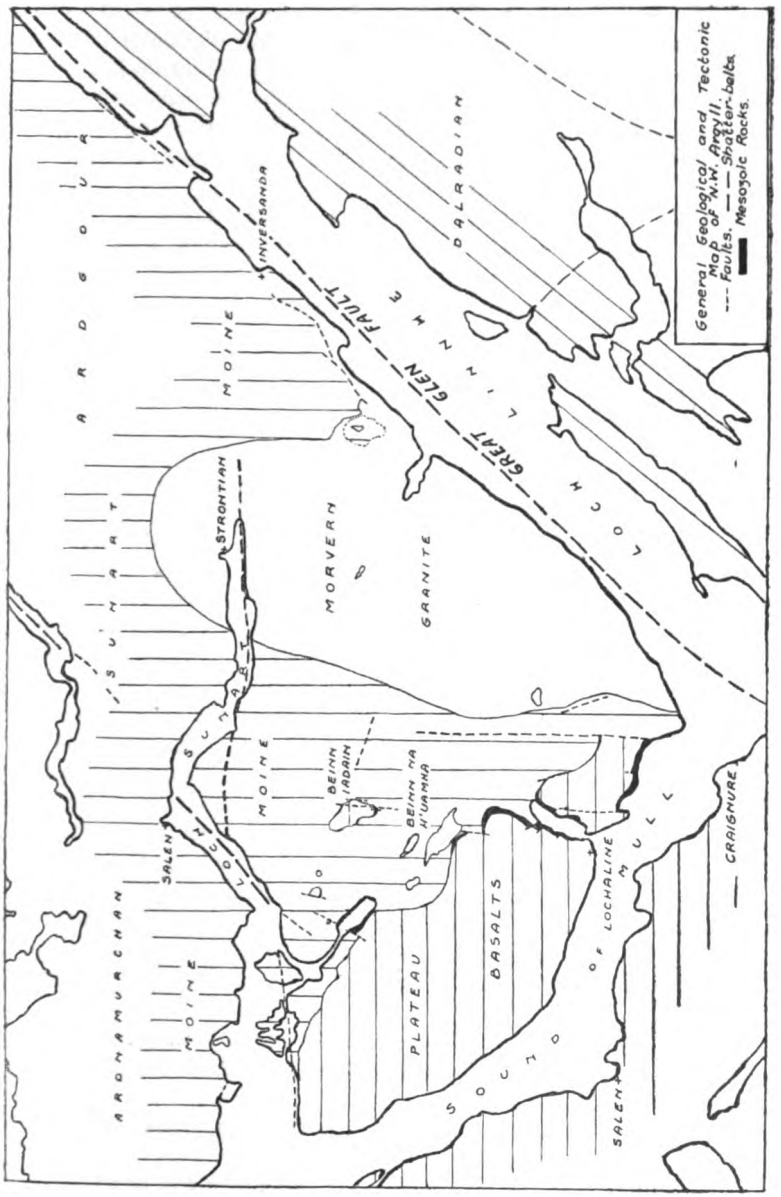


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In the region of the Arienas-Teacuis valley the faults cut across its line almost at right angles, *e.g.*, the Allt a' Choire Fault—whether it be taken as a continuation of the Beinn na h'Uamha Fault or of the main Beinn Iadain Fault—is responsible for the greatest width of Loch Arienas, the line of the fault being at a high angle to the greatest length of the loch, and incidentally at the same angle to the valley itself.

Again, the fault which forms the western boundary of the Loch Teacuis Mesozoic outcrop makes a right angle with the line of the valley, and is perhaps continuous with the Rahoy Fault.

The Beinn Ghormaig Fault runs roughly parallel to the last, but has a more northerly trend.

Of the N.–S. step-faults on Beinn Iadain, the most easterly shows marked dragging of the lavas on its W. side. The next two (westward) have also a considerable displacement, but the other five observed are only minor dislocations of a few feet. Erosion has been so active since the faulting took place that stepping of the surface is only seen in a few cases, *e.g.* on Beinn na h' Uamha, and (slightly) on Beinn Ghormaig, and in the gneiss E. of Lochan Beinn Iadain.

Among the E.–W. faults, that cutting the island of Carna is conspicuous. It is in the nature of a wrench fault, displacing the gneiss horizontally for over ¼ mile, and trending at first W.S.W., and then E. of Auliston Point, almost due W.

Another E.-W. line of dislocation which is not marked by the bringing into juxtaposition of rocks of different types but by a line of cliffs, gorges, and depressions called in Gaelic *glac*, occurs in the northern part of the area. The southern shore of Loch Sunart opposite Strontian is steep, and this feature is continued westward (with the exception of the bay between Achleek and Liddesdale) past Laudale to Coire an t-Sneachda. From that point past Lochan Dhonnachaidh to Camas Salach, it takes the form of depressions and gorges, and a possible continuation is found on the Ardnamurchan side in Allt Camas Inas and the head-waters of the burn to the W.

At Lurga in Gleann Dubh there is another E.-W. fracture. Westward it is seen in the head-waters of the Eas Ruadh and near Meall Lochan nan Lorg.

Numerous small faults occur in the granite area and are usually occupied by streams.

Some late but minor faulting has affected a few of the N.W.

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dykes, *e.g.* one on the N. side of Loch Teacuis, E. of Carnliath, is faulted horizontally for one foot, the fault being marked by crushing and dragging of the dyke-rock along its line; another, a few yards to the E., and 3 ft. wide, is faulted a distance equal to its own thickness.

The N.E.–S.W. faults are only common in proximity to the Great Glen Fault, to which they are parallel. They form lines of weakness along which small fault-intrusions of granite have been injected, *e.g.* S. of Inversanda and N. of Ardgour.

## Physiography.

### *General.*

The Pre-Palaeozoic foundation consists of Moine gneisses and schists which are highly crystalline and give rise to rugged hummocky hill-masses. The hard resistant nature of these rocks is reflected in the name applied by the Celtic inhabitants to the country lying between the Arienas-Teacuis valley and Loch Sunart, *viz*:—' Taobh Garbh ' which means ' the rough side.'

The Morvern Granite which forms the eastern portion of the area, is of two kinds—a pink and a grey. The weathering of these varieties is, to a certain extent, different, as the grey type is generally coarser and the phenocrysts larger than in the pink.

The sedimentary series, though unimportant from the point of view of areal extent, are exceedingly important topographically. Their outstanding feature is of a negative character—they form an easily weathered foundation for the overlying basalts.

The Kainozoic Plateau lavas, which cover an extensive area on the Sound of Mull coast, show characteristic ' trap-featuring.' They rise with a gentle slope from the sea inland, attain a height of over 1800 ft. in Sithean na Raplaich, and fall precipitously into the Arienas-Teacuis valley.

### *Boundaries.*

Even after a cursory examination of the Ordnance map, one cannot fail to notice that the boundaries of the peninsula of Morvern lie along geographical lines which are characteristic of Scotland as a whole.

The first or consequent drainage-system, with a trend approximately N.W.–S.E., is responsible for two of these bounding lines. The sound of Mull and the eastern part of Loch Sunart together with Glen Tarbert, though now modified to some extent by



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faulting, may be safely regarded as the channels of two ancient and almost parallel consequent rivers.

The Sound of Mull is over 20 miles in length, and has a maximum width of 3 miles (Clach na Criche to Salen, Mull), and a minimum of about 1¼ miles (Dun Ban to Rudh' an t-Sean Chaisteal). Its average depth is between 30 and 40 fathoms, and there are three larger and three smaller basins, each over 50 fathoms. The largest of these, lying along the line of the Sound between Ardtornish Point and Eileanan Glasa, is about 7 miles in length. This deep is cut off from another lying to the S.E. by a submarine ridge connecting the Sgeir Mhic Chemhain with Ardtornish Point. This might suggest a continuation of the Craignure Anticline across the Sound of Mull into Morvern. H.M. Geological Survey, however, suppose that that feature again strikes the Mull shore near Ban Eileannan, the axis of the anticline having been bent more to the W. Whether or not this is the case, the parallelism of the Mull shore between Craignure and Scallastle Bays with the Morvern shore between Ardtornish and Loch Aline is certainly suggestive. A probable explanation of the ridge is as follows. An important fault with a downthrow to the W. brings lavas from over 400 ft. above sea level to slightly below sea level at Ardtornish (Lower Lias limestones appear below h.w.m. about 1 mile to the N.W.). It seems feasible to suppose that a fault of such magnitude will be continued under the sea for a considerable distance, and that it might be connected with the dislocations of the Craignure region. The presence of this fault also explains the rapid deepening of the sea-floor off the W. coast of Ardtornish Point. The line of cliffs, now only found to the E. of the fault, was no doubt continued westward before the faulting occurred. Before that time of course, the cliffs would occupy a more southerly position relative to the distance subsequently eroded. The submergence of the western end of these cliffs on the downthrow side of the fault would account satisfactorily for deep water being found so near the shore.

The Inninmore Fault, with a downthrow of at least 1000 ft. to the W. is an even more inportant and more noticeable feature of this region. It approaches the coast with a trend slightly W. of S., and, after skirting the W. side of Eilean Rudha an Ridire, probably becomes more easterly until it again turns almost S. in the neighbourhood of the Great Glen Fault.

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The western part of the Sound of Mull, that is, N.W. from Fishnish, is more typical of the old consequent drainage channel, owing to the fact that here less faulting has taken place. A transverse section shows its profile to be of the type named 'gutter' by Prof. Gregory who applies this term to mature valleys with gentle slopes on either side. Indeed the ground rises so slowly and regularly from the sea that when sailing up this part of the Sound, the scenery gives the impression of monotony. This is particularly true of the Morvern slope, as there the even hill-side is continued unbroken from Loch Aline to Auliston Point, a distance of over 12 miles. With deep Glen Forsa and the towering peaks at its head, with Glen Aros and the low pass to Loch na Keal, the Mull side, from a scenic point of view, compares favourably with the northern shore.

Loch Sunart is over 20 miles long, and trends, at its mouth E.–W., in its middle reaches N.E.–S.W., and in the eastern portion first N.W.–S.E. and then E.–W.

Though the eastern half of Loch Sunart together with Glen Tarbert has a direction more E.–W. than N.W.–S.E., it is considered to be the line of an old consequent valley somewhat modified by faulting or by shattering. The depth of the inner basin (N.W. of Liddesdale) might be put forward as an objection to this supposition, but the deepest end of this basin coincides with the western boundary of the Morvern Granite. As the granite is porphyritic and therefore easily weathered, especially when compared with the Moine gneiss into which it is intrusive, it is not hard to imagine that, in the course of the ancient river, the water leapt down a high gneissic wall into a deep pool cut in the less resistant igneous rock. The faulting principally affects the Morvern side of the Loch. The steepness of the southern side as compared with the gentle slopes of the northern shore cannot be explained as due to any agency other than faulting. As already stated no actual line of fault is encountered until it cuts the coast W. of Laudale, whence it is continued through the depression of Glac Eannich, and the gorge of Allt a' Chamais Shalaich. That there has been movement along this line is shown by the presence of slickensided areas in these two localities. The course of the River Carnoch from about Achnalea upward, appears to be guided by the eastward continuation of this line. From the Glen Tarbert col to Laudale the fault is therefore hypothetical, but the feature, as seen from Meall a' Chuillinn on the N. side of the glen, is most striking and suggestive.

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The N.W.–S.E. portion of the loch is a typical 'gutter' consequent. Towards the N.W. end it is modified by the N.E.–S.W. middle reach, and becomes deeper towards that reach.

The second set of geographical lines has the N.E-.S.W. trend characteristic of the Caledonian earth movements. In northern Argyll at least four important features follow this line, *viz*:— Loch Awe, Upper Loch Etive, Loch Linnhe, Loch Shiel and the middle reach of Loch Sunart. The first two lie without the Morvern area, but serve to emphasise the importance of this N.E.–S.W. set. As Loch Linnhe forms but a part of the most important and one of the best known of the topographic features of Scotland, it is not necessary to enlarge upon it. The Great Glen Fault must pass very close to the Morvern shore, as there the ground is very steep both above and below sea level and the rocks are in a shattered condition. As already mentioned, numerous subsidiary faults run approximately parallel to the main one, and in one case such a fault is partly responsible for the small valley between Cilmalieu and Inversanda.

Loch Shiel and the middle reach of Loch Sunart lie along a line which, though much less noticeable than the last, can be followed for almost as great a distance. Beyond the head of Loch Shiel it may be continued by way of Strath Affrick as far as the Ord of Caithness. In a S.W. direction, where it apparently cuts the coast of Morvern, three diverging faults are developed. The most important of these (as already described) takes on a more westerly trend, being first W.S.W., and then almost due W. It cuts across the island of Carna, where it causes a considerable horizontal displacement of the Moine rocks,and may be continued through the isthmus of Oronsay and Loch na Droma Buidhe. Further W. it is responsible for the abrupt cliffs just E. of Auliston Point. The other two faults cut the coast near Camas Glas. The line of one, the more easterly, is occupied by the Allt a' Chamais Ghlais, and forms the eastern boundary of the Rahoy Mesozoic outlier. The remaining fault lies about ¼ mile to the W. and is likewise occupied by a stream. Though the ground between Loch Shiel and Loch Sunart sometimes exceeds 500 ft. in altitude, it is significant to find the rocks in that position exhibiting signs of movement. Two streams draining into Loch Shiel, Allt Camas Bhlathain and the upper reaches of Allt na h' Atha duibhe, flow in gorges, the erosion of which they have found easy as they lie along shatter-belts. On both sides of Sailean nan Cuileag (E. of Salen) the

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garnetiferous gneiss is intensely folded and faulted, while on the W. side of Salen Bay and near Resipol the Moine rocks show their usual simple highly inclined dip of foliation.

## The Morvern Plateau.

Whether one views Morvern from the mainland at Oban, Appin, or Ardnamurchan, or from the islands of Mull or Lismore, the one feature which always attracts attention is the remarkable uniformity in the level of its high ground. The general height of the plateau is roughly about 1000 ft. above sea level, an altitude which is common also to the Lorne Plateau, and to those of N.W. Mull, Ardnamurchan, and Western Sunart. To the N.E. this plateau merges gradually into the main Highland Plateau which, on the N.W. side of Loch Linnhe, stands at between 2000-3000 ft. above sea level. In the whole district the only hills which stand out from the surface of the plateau are the "basalt caps" which as will be seen later, owe their prominence in a large measure to the almost insignificant thickness of sediments below the lavas.

On a closer acquaintance with the plateau it is found to be highly dissected in the interior. Practically the only breaks occurring in the peripheral wall of Morvern are formed by the mouths of the three great passes which give the district its name. These glens, together with their tributary valleys, have cut up the area considerably.

## Topography in Relation to Rock-Types.

As already stated, the Moine rocks give rise to rugged hummocky hill-masses. This is characteristic of the series as a whole, but in addition, distinctions can be drawn between the surface features arising from the various types of gneiss, *e.g.* the difference in the weathering of the psammitic and pelitic types is quite appreciable. The former, being more even grained, yields fairly smooth rounded knolls and hills, whereas the latter, with its richness in such minerals as garnet, gives rise to much more irregular and 'knobbly' surfaces. The distinction is not striking where there is a transition, but when the two types are brought together by a fault (as in Carna) the difference is at once apparent. The colour of the vegetation growing on the soil derived from the gneisses is also characteristic: in spring it is pale or dull green; in autumn, yellow and brown.

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In the products of their weathering there is not much difference between the gneiss and the granite. Both are rich in quartz, and both give a sandy soil. Their power of resistance to weathering agents, however, is very different. The granite is more easily disintegrated because of the range in the size of its constituents. Between the pink and the grey varieties of the granite also, this quality makes itself apparent. The red rock forms much rougher and higher hills than the grey. The granite shows the effects of ice-sheet glaciation most distinetly, and nowhere is it more noticeable than along its western boundary with the gneiss. The contact is marked by a line of gneiss hills flanked by a depression in granite. This depression would no doubt be initiated when the boundary was first exposed. The junction between the two rocks would naturally form a line of weakness of which the subsequent drainage would take full advantage. The line of gneiss hills trends a few degrees W. of N., and the ice flow (lower layers) coming in a N.E.–S.W. direction, impinged against his wall and was deflected more to the S. until the hills became so low that it over-rode them. In this over-riding it was assisted by a further factor. On the southern part of the boundary, the direction of flow became more westerly because the pressure exerted by the division of the ice-sheet at Craignure became sufficiently great to force the ice-sheet over the gneiss—otherwise the depression would probably have been continued south right to Rudha an Ridire.

The sedimentary rocks play an important role in the moulding of the Morvern landscape. The Inninmore of Ardtornish and of Sithean na Raplaich, the steep cliffs on either side of Loch Aline, on Beinn Iadain and on Beinn na h'Uamha, are all due to the presence of a thin layer of sediments sandwiched between the great thickness of lava and the country gneiss. At the Inninmore of Ardtornish faulting has taken place, but that faulting is at right angles to the line of the cliffs and is therefore not responsible for them. Indeed, the most westerly fault is the cause of the gentle slopes of Ardtornish Point. Sediments are not found on the Sound of Mull coast W. of Loch Aline and there are no cliffs—only the small raised beach scarp. At Fountainhead (E. of Loch Aline) there are cliffs which some may attribute to faulting, but from examination of the ground it becomes apparent that though faulting has occurred, it was not until the stream had cut down to the sandstones and shales that the formation of the

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cliffs started. Again, at the All a' Choire Fault lavas are in juxtaposition. There is no line of cliffs until the sediments appear, and then, on the E. side of the fault, there is the scarp of Sithean Achadh nan Gamhna. With the exception of the E–.W. fault at Auliston Point all the important lines of dislocation cut the lines of the basalt cliffs at high, and usually right angles. Such examples could be multiplied indefinitely. The cliffs are almost always due to the rapid weathering and disintegration of the sediments. The only case where they stand out because of their own durability is found to the S.W. of Claggan, and there it is due to the Trias cornstone being more resistant than the Lower Lias limestone and shales. The Trias forms a small scarp which is only exposed at intervals, and is noticeable because of its being inclined at an angle to the line of the basalts above.

The Plateau Basalts, when they are not subject to the undermining influences of the stratified rocks, give rise to their characteristic 'trap-featuring.' This type of scenery is best seen on the plateau W. of Loch Aline. There the slope is uniform and is only broken by the small scarps which represent the resistant centres of the various flows. On this plateau the distance between these scarps is often so great that the ground between is almost level and is accordingly badly drained. A vegetation of heath and peat results from these conditions. When drained, however, the lavas are covered by a most luxuriant verdure which furnishes some of the finest grazing in N.W. Argyll. The landslip and talus slopes form prominent features of the landscape; they result from the presence of the sedimentary rocks.

Another noticeable point with regard to the basalt plateau is the 'lineated scenery' produced by the N.W. dykes. This feature is mentioned in the Memoir for Sheet 44 (p. 358) in connection with northern Mull, and it is no less true of the plateau on the N. side of the Sound. It is best developed in the Crois Bheinn area.

The lines of many dykes are followed by streams; sometimes the dykes cut across the streams and cause waterfalls. An instance in which both these points are illustrated is found in the Allt na h' Airidh between Achleek and Liddesdale. Part of the lower course of the burn flows in a gorge eroded along a N.W. dyke. At the top of this section there is a fall of some 65 ft. in height caused by an E.–W. felsite dyke which cuts across the line of the burn. In the Eas Ruadh, and in the Black Water a short distance above

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Acharn, felsite dykes are again responsible for considerable waterfalls. A basalt dyke trending W. of N. cuts the Barr River just N. of Barr, and below is the deep pool called 'Stangadail' which is famous in old stories connected with the Norse invasions.

As faults generally produce lines of weakness it is not surprising to find the position of most marked by a depression and drained by a stream flowing in a gorge. The famous Inninmore Fault is a typical example. Its line is taken advantage of by five different burns, while the course of several more have been to some extent affected by it. In the case of the Upper Sunart E.–W. fault this is again seen, while the shatter-belt connecting Loch Shiel and the middle reach of Loch Sunart is still another and more important instance. The most important feature about the faulting in the district is that it often brings into juxtaposition rocks which are of entirely different composition, and therefore give rise to quite dissimilar types of topography and vegetation. The Inninmore Fault is again the best known example, but the point is well illustrated in many places all over the district. It is seen on Beinn Iadain (E. side), and Beinn Ghormaig derives its name from its deep green vegetation which is in such marked contrast with that of the Moine around. Seen from the N., the line between the two on the W. side (the faulted side) is most distinct. On the northern slopes of the hill the scree from the lavas gives rise to 'streams' of green which flow over and dissipate themselves on the more barren gneiss.

### The "Mor bhearna" or Great Passes.

The country has undergone such tremendous denudation that the recognition and interpretation of valleys as being the relics of the early drainage system is a problem which presents the greatest difficulty. That such valleys antedate the formation of the Morvern Plateau seems so obvious that it needs no comment.

The most important valley is that containing the chain of lochs from Loch Aline to Loch Teacuis. From Lochaline to Claggan, *i.e.* about one third of its total length, the trend is N.–S., while the remaining two thirds follow a N.W.–S.E. direction.

Loch Teacuis, though a sea loch, would with a slight elevation, be converted into a fresh-water loch, as the narrows on either side of Carna (E. Caol Charna, W. Caol Achadh Lic) and the narrows W. of Rahoy are very shallow and constricted; in fact, the water

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at these points during ebb and flow of the tide is more like a river in flood than part of an arm of the sea. Partly owing to the heavy rainfall and partly owing to the narrow entrance at Caolas Rahuaidh, the waters of the loch inside that point are sometimes, during a hard frost, completely frozen over. When the thaw comes, an ice-jam, comparable to those seen on the rivers draining into the Arctic Ocean, is formed at the 'rapids' of the inner narrows. The contours of the valley sometimes approximate to those of the 'gutter' type, but generally the slopes on the southern side are much steeper owing to the basalt scarps. At Barr and at the head of the loch there is an extensive development of the '25 ft.' raised beach.

The surface of Loch Arienas is 36 ft. above sea level, while that of Loch Doire nam Mart is only .6 of a foot higher. They are connected by a small stream about one third of a mile long, which, having so little of a fall, meanders most of the way through an almost level bog. A depression to the N.W. of Loch Doire nam Mart was occupied by a small loch, but it is now quite filled in by silt and peat accumulations. A similar fate is in store for Loch Doire nam Mart itself—and that at no far distant time—as its waters can only be reached at a few points by dry ground. The margin of the loch is almost entirely surrounded by marsh, and reeds and bulrushes grow out into the loch for a considerable distance. Its maximum depth is only 48 ft.

Loch Arienas is nearly two miles in length, and has a maximum breadth of five-eighths of a mile. Almost at the point where these two lines cross is the maximum depth of 116 ft. The shores of the loch are, with the exception of a small patch at its head, quite free from marshes. They are for the most part rocky, but large stretches of sand occur, *e.g.* near Camsa Allt a' Choire, and at the outlet. The former occurrence is interesting in that sands of three distinct colours are present, *viz.*, very dark (almost black) from the lavas, almost white from the Mesozoics, and yellow from the moine. The sands at the outlet are dominantly from the gneiss, and cover a considerable area.

Loch Arienas is drained by the River Aline which flows into Loch Aline. The river, for a short distance after it leaves the loch, is called in Gaelic 'Gearr Amhinn'— the rough water. The significance of this name is obvious only under certain conditions. If heavy rain has been falling on the catchment area of the rivers draining Gleann Dubh and Gleann Geal, and little or none on the

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Arienas basin, the flood waters from these rivers, which join at Acharn, flow into Loch Arienas against the outward stream, and continue to do so until sufficient ' head ' of water is accumulated in the loch to force them back and divert them once more to their normal course. It can be imagined that the name ' rough water ' is aptly descriptive of such a contest between river and loch. The river Aline is two miles long and falls 36 ft. in that distance. There are two areas of alluvium along its course, and these form the chief arable ground in the Aline drainage-basin. Towards its mouth the valley narrows until the river just before it enters the loch, is flowing between walls of rock, these walls are not high, but they form practically the only solid rock exposed along the actual course of the river.

Loch Aline called forth the highest praise that Macculloch would allow himself to utter when describing Morvern. Writing (to Sir Walter Scott) of the northern end of the loch, he says " Here, indeed, it deserves the name of beautiful." The character of the topography at the N.E. end of the loch is that of typical Moine country, while on either side, the ' 25 ft.' raised beach is backed by steep cliffs capped by lavas and everwhere clothed with trees. The sides are cut almost at right angles by several faults which are not without their effect on the formation of the basin. The most northerly fault probably crosses the loch along the line which is exposed at low water and which marks the beginning of deep water. The entrance of the loch is narrow (though not so narrow as that of Loch Teacuis) and the tides run strongly through. The scenery on either side of the entrance gives no hint of " green Loch Aline's woodland shore " within.

The presence of remnants of the 100 ft. raised beach along this valley shows that the ground lying to the S.W. was an island separated from the " mainland " by a narrow sound. (The word ' mainland ' is put in inverted commas because it would only be part of a larger island, bounded on the W. and N. by a strait containing the basins of Loch Shiel and Loch Eil). During intermediate raised beach times that island would be a peninsula connected to the rest of the district by an isthmus which was perhaps uncovered only at low water.

More recently the deep parts of the sound were left as a chain of lochs, at first only three in number—Loch Teacuis, a large loch comprising the present Loch Arienas, Loch Doire nam Mart, and

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another smaller one to the N.W. and Loch Aline; and finally as they are at present.

The valley of Loch Uisge and Amhainn na Coinnich, in the N.E. corner of the district, has a N.W.–S.E. trend. Its form, particularly in the lower reaches, has been modified greatly by ice action and by faulting. As it now lies entirely within the granite outcrop it is difficult to determine the position and extent of any dislocation. It is possible however, that the important N.W. fault seen in the Pass of Brander, Gleann Salach, and Strath Appin is continuous across Loch Linnhe to the basin of Loch a' Choire and the valley to the N.W. A minor fault apparently on the same line occurs on the S.E. slopes of Beinn nam Beathrach. Just at the head of Loch a' Choire the valley has been very much widened by the action of corrie glaciers working on the N.E. slopes of Beinn Mheadhoin. It is certain that there were three of these glaciers, but there may have been two smaller ones in addition. To the N.W. and beyond Loch Uisge the valley is largely filled with morainic material, while the slopes on both sides are covered with drift and erratics to a height varying from 600-1200 ft. above sea level. The profile of the valley at this point shows it to be mature. The col separating it from Gleann Dubh is a typical, though small, wind-gap.

Even from an examination of the Ordnance map it is apparent that the upper reaches of the Black Water are obsequent, *i.e.*, they lie along an originally consequent line but their waters flow in the opposite direction. In contra-distinction to the valley just described, Upper Gleann Dubh is highly glaciated and has a typical U-shaped profile. In addition it is almost free from glacial deposits. Lower Gleann Dubh, from the bridge southward, is subsequent, as the burn flows along the strike of foliation of the gneiss.

It is perhaps possible to trace the course of events in the history of Upper Gleann Dubh. Before the Ice-Sheet glaciation it is probable that the consequent stream flowed E. from the neighbourhood of Beinn Iadain, if not from further W. The burn joining the Eas Ruadh at Corrospine may be considered as a southern tributary of the river, while in the Lurga burn and the head waters of the Eas Ruadh may be the remnant of another—if not the main river itself. Part of the Allt Clachaig is consequent; also the burn at Achagavel and the next one to the N. It has already been stated hat as the granite boundary became exposed a subsequent

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drainage system developed along that line and formed a depression lying in the granite. When the main glaciation occurred, the ice found in the gneiss hills, the consequent gap, which was more in line with its own direction of flow than was the subsequent. Thus a branch of the under-layers of the ice sheet scoured and scooped out Upper Gleann Dubh, and to the S.W., passed on to the hills north of Acharn. When the ice disappeared it left a lake which in time was drained by the subsequent Lower Black Water, until at present all that is left of it is Loch Clachaig. The obsequent head-waters of the Black Water, eroding in granite country, are rapidly extending their catchment area.

In the Eas Ruadh is an example of a subsequent stream which has captured the head-waters of a consequent—the Lurga Burn.

Another interesting but incipient example of this is seen on the eastern slope of Meall a' Chuillinn (Liddesdale). A small consequent stream, flowing down the slope from gneiss to granite, is, after heavy rains, beheaded by what is normally a mere trickle draining along the contact. After the rain has passed the stream is again supplied from its head-waters, but this state of affairs cannot last for any length of time.

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## No. VII.—Buried River Valleys in Clydesdale. By James Stark.

(Read 10th March, 1927; issued 7th January, 1928).

In a paper[1] on the "Surface Geology of the Falls of Clyde District" read to this Society in 1899, the present writer pointed out that the Clyde Valley is wide and open as far up as the District in question, but that at Braxfield, it suddenly assumes the form of a deep, narrow, and in places, rocky defile, which continues for half a mile till it ends in a spacious basin, through which the river flows with a comparatively gentle current for over a mile, past the village and mills of New Lanark. At the head of this wide hollow the river emerges from a second defile bounded by precipitous rocky walls over 100 ft. in height. Some 400 yards above the entrance to this defile, at a sharp bend of the river, occurs the Fall of Cora Linn, consisting of two broken leaps of about 30 and 60 ft. respectively. Above this the river toils for half a mile along a series of rapids till we come to Bonnington Fall, a single leap of about 35 ft. Above this fall comes another, but shorter series of rapids, where the stream flows over broken edges of shelving sandstone: and beyond this the rock, for several miles, is no longer seen, the river pursuing a placid course through an alluvial tract of ground, between sloping banks and kames of sandy and gravelly drift.

Near the lower end of this quiet reach the Clyde receives the waters of the Douglas from the S.W. at an elevation of about 580 ft. above sea level, and from this point to the foot of Cora Linn it descends about 190 ft. From there to the foot of Stonebyres Fall it descends about 190 ft. more, which gives a total fall of about 380 ft. in a distance of rather over four miles, while the general level of the plateau in which so deep a trench has been excavated remains fairly uniform.

Comparing the wide open Valley of the Clyde below the falls (including the wide basin at New Lanark) with the narrow precipitous gorges of the Falls, it is obvious that the former are constituent parts of the ancient Valley, while the latter are new channels

[1] Trans. Geol. Soc., Glasgow. Vol. xii., p. 52.

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dating subsequent to the glacial period. During at least the later part of that epoch, the flow of the glaciers from the Southern Uplands appears to have approximately coincided with the general north-westerly course of the Clyde, but in this district the river for a distance of over five miles, takes a wide sweep to the S.W. This being right across the flow of the ice, the Ancient Valley was here completely filled up with glacial debris, over which the river, after the melting of the ice, was compelled to find a new channel. In so doing, it encountered in places the solid rock which formed the boundaries of the Ancient Valley, and has since worn out the rocky gorges by means of three falls, the present positions of two of which are at Bonnington and Cora Linn, the third, which cut the gorge at Braxfield, having long ago worn itself out. As soon as this obstruction had thus been removed, the debris filling that part of the Ancient Valley up to the Bonnington gorge would speedily be cleared out, and a new fall started where the Bonnington one had begun, but on a lower level. This youngest of the falls is now working in the Bonnington gorge and has cut its way back to its present position at Cora Linn.

A sketch map accompanying the former paper suggested the probable pre-glacial courses of the Clyde and Douglas Water, the confluence of which was indicated as a couple of miles below its present position, and this suggestion has recently been confirmed by the operations of the Clyde Valley Electric Power Company who are at present harnessing the Falls for the generation of electric energy to be distributed over the Upper Ward of Lanarkshire, and also to supplement their steam installations at Motherwell and Yoker.

An aqueduct or tunnel is being driven from the intake sluices some distance above Bonnington Fall to convey the water to a Power Station, some 450 yards below Cora Linn. The tunnel, which is half a mile long, by ten feet in diameter passes through red, blue, and grey sandstones till it encounters the debris filling up the buried Ancient Valley, through which it is being carried, for the last 450 yards, by means of segment rings of cast iron to a surge-tank, close to, but about 180 ft. above the level of the Power Station. This Station is situated on what is suggested to be the pre-glacial confluence of the Douglas Water with the Clyde.

The material filling up the Ancient Valley is composed of well-rounded gravel, sand and clay, while borings along the line of the tunnel shew that the same loose deposits cover the rock surface

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above the Falls to a thickness of about 60 ft., besides filling up the Ancient Valley. These are waterlogged at a depth of 30 to 40 ft., and a 60 ft. shaft has been sunk to deal with the water and enable the segments of the iron casing to be bolted together, thereby disclosing a fine section of the gravels. From the surge tank the water will be conveyed to the turbines in the Power Station by two steeply inclined steel pipes 6 ft. 6 ins. diameter, under a head of about 190 ft. from the inlet sluices above Bonnington Fall.

At Stonebyres a similar tunnel has been driven through solid rock for a distance of 500 yards, from the inlet sluices above to a Power Station below the Fall, affording a head of water of 97 ft.

The energy available when this great undertaking is completed is estimated to be about 13,500 H.P. below Cora Linn and 7,500 H.P. at Stonebyres.

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No. VIII.—Some Geological Notes on Three Districts of Northern Scotland. By A. G. Steavenson, M.A. (Cantab).

(Read 14th April, 1927; issued 14th January, 1928).

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These notes are based on observations made in the years 1920 to 1925.

Some of the place-names occur only on the 6-inch Ordnance map.

Distances, unless otherwise mentioned, are measured in a straight line, and not along the roads.

## I. The Stornoway Torridonian Outlier.

### 1. Tectonics and Thickness.

The town of Stornoway is situated on the western edge of an area of chocolate-red conglomerate, much of the surface of which is now beneath the sea. The visible portion measures five miles from E. to W., and ten miles from S.S.W. to N.N.E. Its structure is simple. The base is seen at its eastern margin in the Eye Peninsula, where it rests upon an eroded and uneven surface of Lewisian Gneiss. The dip is very constant in direction all over the southern and greater part of the outlier, being always between W. and N.W., usually W.N.W. North of Coll Sands the dip is N.W. or even N.N.W. In amount (with a few local variations) the dip decreases steadily from the base, near which steep dips of from 30° to 45° prevail upwards to the western margin, where the conglomerate is faulted down against the gneiss of the interior of the island. Near the boundary faults (i.e. in the highest beds remaining) the dip is only from 10° to 15°.

The gneiss hills rise in an irregular escarpment above the lower ground occupied by the conglomerate, which appears as a faulted-down coastal strip. The western margin is formed by a system of four intersecting faults, two of which run nearly N. and S., and the other two W.S.W. and E.N.E. Three of the faults were actually seen and proved, and the structure visible seems to require the fourth, which is concealed under deep peat and drift. Although much of the country inland is covered by superficial deposits, the coast sections, which are very clear and fine, pass

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in such various directions through the conglomerate that most of the outlier is laid open in a highly satisfactory manner.

The conglomerate is not only in a very fresh and unaltered condition, but although it has been tilted, it is otherwise curiously undisturbed. It is nowhere bent or folded, and, away from the boundary faults, there seems to be no faulting of any but the most trifling extent. There is sometimes a shift of a few inches along joints, and there is a small N.W. fault with a little disturbance of the rocks on the N.W. coast of Eye, near Garrabost, but that is all. If, however, the large N.N.W. and S.S.E. fault which bounds the outlier N. of Coll Sands continues S. in the same line in the conglomerate under the Coll alluvium and dunes, and under the water of Broad Bay, it may well pass through Branahuie Banks (the spit of sand and shingle connecting Eye with the mainland), and as it throws down to the E., it would cause a material repetition of strata.[1] It is just at the Banks that the one considerable gap occurs in the otherwise almost continuous coast sections, and the outcrop of the fault may have been shifted considerably by the E.N.E. fault which intersects it at the north end of Coll Sands and may pass along the valley S. of the main road to the sea near Buaile an Ochd. The conglomerate is of so uniform a character throughout that it is nearly impossible to tell from the coast sections whether a repetition of strata really occurs. However, even if full allowance is made for a possible repetition by a fault through Branahuie Banks of nearly all the conglomerate which appears in Eye a remarkable feature of the outlier is its great apparent (and I believe, actual) thickness. I cannot make it to be less than 5,000 feet; and if there is no repetition it is about 10,000 feet thick: a truly impressive mass of conglomerate, and in the highest remaining beds against the boundary faults there is no sign that the top of the formation is being approached.

## 2. Character of the Rocks.

(*a*) General. All over the outlier the rocks are of a remarkably uniform general character, so that one description will serve for the whole thickness. A few local variations will be noted in the next paragraph. By far the greater part of the formation is a conglomerate of gneiss pebbles, superficially stained red-brown, and lying nearly or quite in contact with each other in a scanty matrix of red-brown or chocolate-coloured loamy sandstone,

[1] *Cf.* Stevens (1914), p. 57.

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usually coarse and often somewhat calcareous. The proportion of matrix to included stones varies somewhat from place to place. The pebbles are usually from one to five inches in longest diameter, although numerous small pebbles and occasional considerable boulders occur. Boulders of more than two feet in length are rare. In many places the conglomerate consists of well-rounded pebbles; at others the stones are sub-angular. The variations pass into each other and seem to be of irregular distribution both in space and time. The rock never passes into a true breccia; the stones are all more or less water-worn and rounded. Where it is unweathered the conglomerate is a hard rock, breaking as readily through the pebbles as around them, and the joints cut cleanly through the included stones. The formation is conspicuously jointed into great roughly rectangular blocks by two sets of nearly vertical joints almost at right angles to each other. The chief joints are on an average about fifty feet apart, and their presence often imparts a marked mural character to the cliffs. Most of the many goes and small inlets seem to have been initiated along strong joints. Where, however, the conglomerate is weathered the stones will pick almost as cleanly and readily out of the matrix as from a modern boulder-clay. The great majority (over 90 per cent.) of the stones are various typical kinds of Lewisian Gneiss, and the rest are quartz-vein material which may well have been derived from that formation. I have often searched for a stone of undoubtedly foreign origin and have never found one. It is safe to state that the stones have in general been derived from the Lewisian Gneiss and may well be of fairly local origin. They are usually arranged quite tumultuously, but occasionally, especially with the larger blocks, there is a tendency for them to lie with the long axes parallel to the bedding.

The conglomerate is divided and the bedding indicated by numerous thin beds of red sandstone. In small exposures inland where none of these occur in the section it is usually impossible to ascertain the direction of the dip. These partings are spaced vertically at most irregular intervals, but are very numerous: sometimes only a few inches separates two bands; again I have seen a thickness of eighty feet of conglomerate without any. The horizontal extension of each band, even the thin ones, is usually considerable, for it is not often that one is seen to pinch out. They vary greatly in thickness, but each band maintains its own thickness with a good deal of constancy. Some are mere partings,

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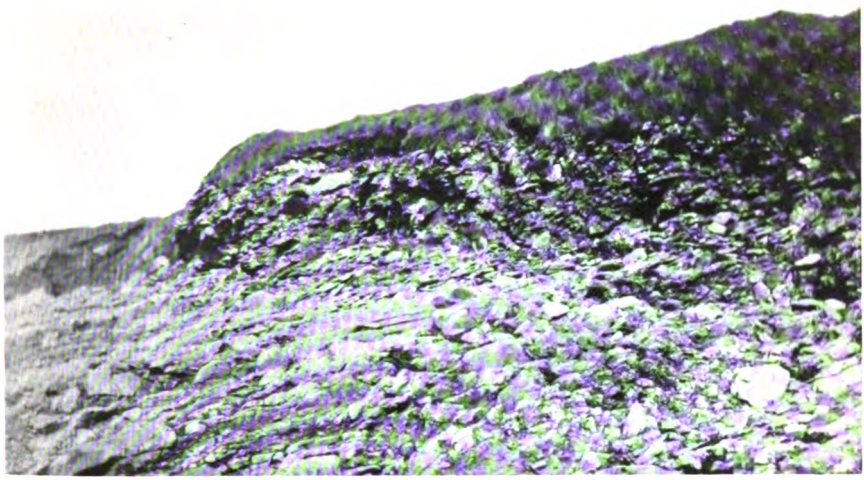

Fig. 1.

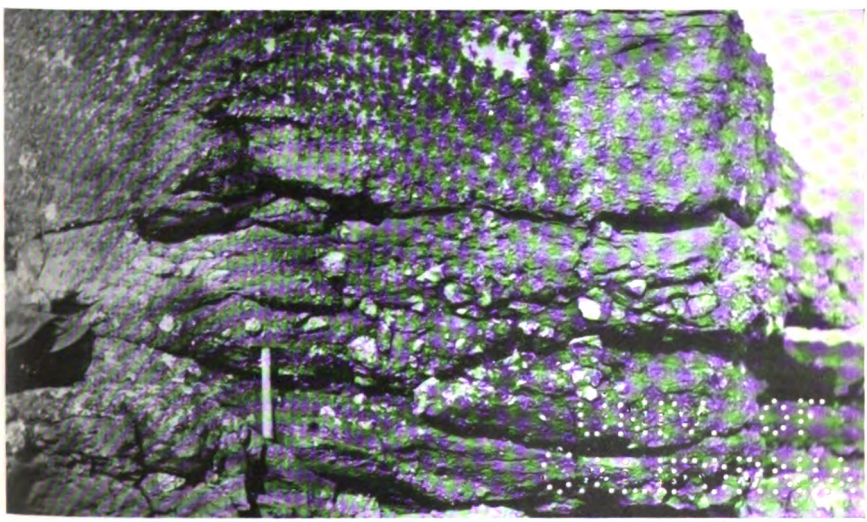

Fig. 2.

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a fraction of an inch thick, and in a few instances a thickness of 12-15 ft. was seen; the usual thickness, however, is from 3-9 in. The junctions with the conglomerate above and below are usually sharp and level. The beds tend to occur in groups. By far the most usual constituent is a rather coarse, chocolate-red loamy sandstone, just like the matrix of the conglomerate. A good deal of fine muddy matter is mixed with the sand grains, and lines of small pebbles are sometimes present. Nearly all the thinner bands consist of this red sandstone, but some are of fine grain, and a few are of hard greenish-grey clay or mudstone. Some of the thicker bands are compound, containing layers of several kinds of sediment (grit, sandstone, clay and shale) of nearly all the colours of the rainbow. Some of the layers are distinctly calcareous. It is a curious fact that although each band preserves a fairly uniform thickness, all except the thinnest are highly false-bedded within themselves, and the thicker ones sometimes show beautiful sections of small wash-outs, stream channels, and sand banks. I have often searched these fine sediments for traces of organic remains but could find none.

(*b*) Local Variations. There is some variation from place to place (quite irregularly distributed, so far as I can see) both in the frequency of the sandstone partings and in the coarseness of the conglomerate. There are two places (both in the highest parts of the formation) where it may fairly be said to pass into a boulder bed, consisting mainly of subangular blocks of gneiss 18-24 in. long. One of these sections is in the low cliff at the N. end of Gress Sands, just E. of Gress Lodge, and the other is a burn section, close to the boundary fault, in the Gleann Druim Niavaig, just under two miles W. of Gress Lodge. In the latter place it is difficult at first sight to distinguish the closely packed and somewhat weathered blocks (towards the west of the section shattered by the proximity of the boundary fault) from a rough surface of gneiss in situ.

Occasionally there are irregular patches or areas of conglomerate measuring from a few inches to several yards in extent, where the stones lie in a matrix of pure white crystalline calcite. These patches are conspicuous, the stones looking very like bubbles in a mass of white foam or soap-suds. At the edges the calcite passes by a gradually increasing admixture of sand into the ordinary red sandstone matrix.

Much the thickest single band of fine sediments observed is at Mol Sandwick Beg on Stornoway Harbour, near the S. end of

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Sandwick village, and 1¼ miles E.S.E. of the Steamer Pier. There are here exposed on the N.W. side of the little bay an interesting and varied collection of beds varying from grits to clays, and in all nearly 15 ft. thick. One band of greenish-grey clay is so calcareous as almost to become an impure limestone.

At two places (one along the line of the straight little N.N.E. valley crossing the western part of the Eye Peninsula from Swordale Bay to Aignish, and the other on the coast N. of Melbost village, from Melbost Point S.E. to Branahuie Banks) the sandstone bands are so thick and numerous that for some hundreds of feet along the coast there is as much sandstone as conglomerate in the formation, a very unusual proportion.

### 3. The Base of the Eye Peninsula.

The base of the conglomerate crosses Eye in a general N.N.E. direction from Swordale to Garrabost. Inland it is nowhere actually exposed but its course (except just around Garrabost village) can be followed closely by means of exposures on both sides. On the N. and S. coasts the sections of the junction are however, very fine. The character of the conglomerate is quite unaltered down to its base, where it rests on a water-worn surface of gneiss, which is highly uneven, whether regarded on a small or large scale. The conglomerate fills up numberless small hollows and open cracks in the gneiss. From the southern section, due S. of the S. end of Swordale village, the junction passes out to sea in a southerly direction, but at the northern exposure, under the extensive landslips near St. Cowstan's Well, it turns along the coast, north-eastwards, for conglomerate reefs are visible at low water at the outer edge of a gneiss foreshore nearly as far as the mouth of the Allt Na Muilne, a distance of about 700 yards, and at two places (one a hundred yards E. of where the junction reaches the coast, and the other about 150 yards N.E. of the Broch and natural arch in gneiss at Dun Mor) conspicuous cakes of red conglomerate, each 100 ft. or more across and 20 or 30 ft. thick, adhere to the cliffs.

The junction is now steeply inclined as a rule, but, allowing for the tilting which the district has undergone, the conglomerate was deposited against a surface which generally sloped at about 20° or 30°, and seldom approached the character of a cliff. It also appears that the central part of Eye is to some

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extent the stump of a gneiss hill of the Torridonian period, for the conglomerate tends to wrap round its N.W. side.

### 4. The Boundary Faults on the West.

Wherever there are exposures on or near the boundary faults (which, unfortunately, is seldom the case, for few parts of Scotland carry a thicker or more continuous mantle of peat and drift than the interior of Lewis) there is every evidence of displacements of considerable magnitude. And this, indeed, must be the case, for, considering the thickness of the conglomerate which is faulted out the throw can hardly be less than several thousand feet.

The following is a list of the exposure of the faults from N. to S.:—

(*a*) The coast section of Geodha Blatha, nearly half a mile S.W. of the mouth of Glen Tolsta. A beautifully clean and clear section, but difficult of close access. At the inner angle of a deep goe in cliffs 150 feet high. Hades about 40° S.S.E. Fine example of a slightly eroded fault scarp in the gneiss just to the E.

(*b*) Burn section in a small gorge on the Allt Raonadale just below a waterfall, a little over 300 yards from its mouth, and only 450 yards W.S.W. of the coast section. Clear and excellent. Hades S.S.E. at about 45°.

(*c*) On the Gress River, nearly 500 yards above where the river enters the alluvial marsh near its mouth. Excellent sections, best in the right bank. Hades nearly S. at 45°.

(*d*) In the sides of the gorge of the Coll River a few yards above its entry into the alluvial marsh at its mouth, and 600 yards due N. of Coll Farm. Sections on both sides, but somewhat obscured by the weathering and slipping of the zone of crushed gneiss. Best in right bank. Hades nearly E. at about 45°.

(*e*) In the Bayhead River at Willow Glen, nearly 500 yards N.W. of the N. end of the town of Stornoway, small exposure, rather obscure and discoloured. Plane hades E. rather steeply.

(*f*) The fault was formerly exposed on the shore on the W. side of the head of Stornoway Harbour, by the Castle stables. It is now covered by the sea-wall, but there are several exposures of the affected rocks on both sides and within a few yards of it.

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It strikes N. and S. The Rev. W. Morrison, of Carr Bridge[1] says (in Mackenzie, 1903) that it is inclined at 60°.

(*g*) At the neck of the Arnish Peninsula, at the mouth of Stornoway Harbour. The fault plane is concealed under a few feet of shingle, but the affected rocks on both sides are beautifully exhibited in close proximity. The outcrop strikes nearly N. and S.

South of Arnish the straight line of the coast, which is very striking to the eye, to beyond Rudha Hurnavy, a distance of 2½ miles, seems to be a result of this fault, which must pass close to the foot of the sloping cliff. The cliff, indeed, is probably to some extent the eroded fault plane.

The zone of crushed gneiss can be very well studied at the quarry a few yards N. of the main road leading W. from Stornoway, 600 yards N.N.W. of the N. end of the town, and 200 yards W. of Manor Farm. The fault is not reached, but the E. side of the quarry must be within a very few feet of it.

At a number of other points there are exposures (usually in the burn sections) of the rocks affected by the faults, which enable the displacements to be located fairly closely. The faults seldom cause any purely local feature at the surface.

At every exposure the appearance of the faults is very much the same, so that the brief general description here given will be sufficient. The variations seem to be only in the width of the zones of affected rocks, but these variations are considerable. The conglomerate (although it is a rock which yields to sea and weather more readily than the gneiss), is at the faults much the less affected of the two. It is not turned up against the fault, and often at first sight looks nearly unaltered, but it is always shattered for several feet and sometimes several yards. The stones remain in position, but each is cracked into small fragments. Occasionally for a foot or two from the fault the conglomerate, although still recognisable, is reduced to a fine breccia in a reddish paste.

The principal plane of the fault, wherever there is a clear exposure, is conspicuous as a sharp, smooth, flat surface, completely separating different rocks.

Next comes a deep zone of completely crushed and ground-up gneiss. In addition to the movement along the main plane, there has been some amount of " give " in this zone also, for it is full of

[1] Mr. Morrison (1885) seems inclined to attribute the deposit to a much later period than the Torridonian, but I can find no strong evidence for this opinion.

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Fig 1.

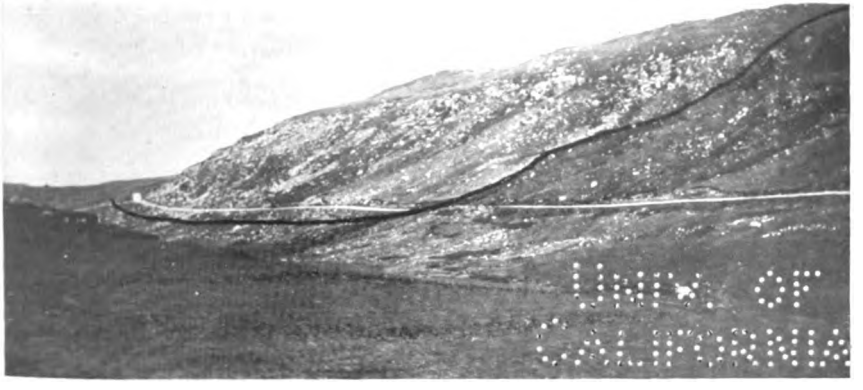


Fig. 2.

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slickensides and little faults. Where unweathered, it is a fine grained rock, breaking with a rather flinty fracture, and mottled red and pale green. It yields to weathering readily and then passes into a clay which can be readily dug out with a spade. In this state it is much used as a binding material on the roads at Stornoway. This crushed zone passes gradually into much shattered, but quite recognisable Lewisian Gneiss; the hard clayey paste begins to contain detached crystals of the harder minerals which have resisted crushing, and the complex banding of the gneiss becomes recognisable. The boundary of this crushed zone towards the gneiss is therefore rather indefinite. The zone varies much in depth, but is never less than several yards, and sometimes its outcrop is a hundred yards wide.

A visible shattering of the gneiss extends to a much greater depth. This also gradually dies away into normal gneiss, but it is sometimes perceptible quite 200 yards from the fault.

The age of these faults is undetermined. Unfortunately the intersection of one of the Tertiary dykes and a fault was nowhere seen, but from their general aspect in this and other parts of Lewis, I suggest that although their inception may have been much earlier, the principal faults of the island last moved in Tertiary time in connection with the break up of the volcanic plateau of the Hebrides.

### 5. Age of the Conglomerate.

The Stornoway Conglomerate cannot be certainly dated, but I have little doubt that it is Torridonian, and it is probable that it belongs to the lowest or Diabaig group of that series. It certainly presents a very different facies from that exhibited in the main Torridonian outcrops on the mainland of Scotland, thirty or forty miles away. On the peninsula of Stoer, however, just over thirty miles due east of Eye, there is a large Torridonian outlier which appears to exhibit a transitional phase.[1] On Stoer the lower part of the Diabaig consists of two beds of conglomerate of pebbles of Lewisian Gneiss, 250 ft. and 15 ft. thick, separated by 200 ft. of red sandstone. Above are more red sandstones and mudstones. As at Stornoway, the beds dip W.N.W. at 20° or more. It seems likely that the conglomerate of Stoer continues

[1] See "Geology of the N.W. Highlands," (*Mem. Geol. Survey*, 1907), pp. 300-303.

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to thicken westwards, until at Stornoway the Diabaig is represented by a single thick mass, with sandstone bands occupying an extremely subordinate position.

It is, perhaps, also worth mentioning that the materials of the sandstone bands have a very Torridonian aspect, and can easily be matched at many places on the mainland.[1]

The thickness of the Stornoway Conglomerate shows that it is a fragment of an important formation, which must have stretched far and wide over the site of Lewis. It must represent a long period of time, for although the beds of conglomerate may have been rapidly deposited, the frequent partings and beds of fine sediment, with their usually sharp junctions, show that there were many intervals of more tranquil and presumably slower sedimentation, or even pauses in deposit. But the same general rhythm of conditions must have persisted unaltered, for all through the great thickness of the formation there is no unconformity or break of general character. I confess that I find it difficult to visualise the physical conditions under which this huge mass of conglomerate was laid down.

[1] The Stornoway Outlier of conglomerate and sandstone has been assigned to various formations. The earlier observers correlated it more or less tentatively with the Torridonian red sandstones and conglomerates of the mainland opposite, these being regarded at first as Devonian, later as Cambrian and finally shown to be Pre-Cambrian in age. Maculloch (1819, vol. i., p. 196), writing about the Stornoway conglomerate, remarks:—"It would be concluded from its general character to be analogous to the old red sandstone, and therefore, like the rock with which I have compared it, to be the first of the secondary strata. Yet this opinion is open to serious doubt." Nicol (1844, p. 240) describes it as "like that of the red sandstone on the mainland, but much harder," his view at this time being that both were Devonian. Murchison and A. Geikie (1861, p. 175) similarly refer it to the same source ("Cambrian") as the red sandstone on the W. coast of Ross and Sutherland. J. Geikie also (1873, p. 534 and 1878, p. 820) speaks of it as "Cambrian Conglomerate." Morrison (1885, p. 235 and 1903) describes it under the title of "Precambrian" and concludes that "the Lewis and Torridon Conglomerates have had neither a community of origin nor a contemporaneity of formation." The New Geological Map of Scotland of Sir A. Geikie (1892), his Geological Map of Scotland (1910), the Geological Survey Map of the British Islands (1906 and 1912) all colour the Stornoway rocks as Torridonian. Stevens (1914, p. 59), following out a suggestion made by Murchison and Geikie in 1861, compares the Stornoway rocks with the Poikilitic Series of the West of Scotland as described by Judd (*Q.J.G.S.*, vol. xxxiv, 1878, pp. 686-695), and suggests a Triassic age for them.—M. MACGREGOR.

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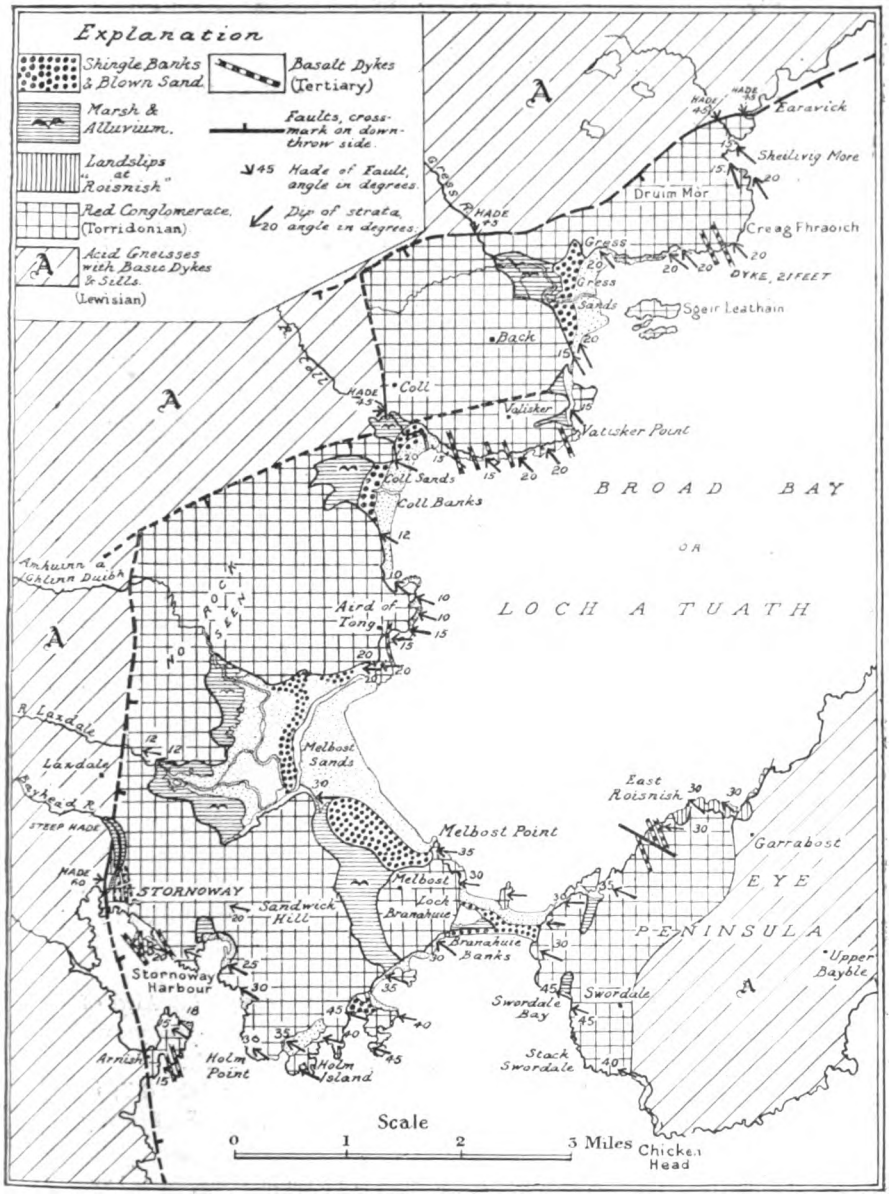


**Fig. 24. SKETCH MAP OF THE STORNOWAY DISTRICT.**

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### 6. Tertiary Dykes.

Sixteen dykes of basalt or dolerite were noticed in the coast sections of the conglomerate, and it is possible that there are two or three more round the coast of Druim Mor at the north end of the outlier, a portion of which I have not examined at low water.[1] The dykes vary from mere strings up to a width of 21 feet. With few exceptions, they are vertical N.N.W. dykes, and I see no reason to doubt that they all belong to the great Tertiary suite so numerous in N.W. Scotland. There are some very fine examples, but they present few special features. Sometimes they are flush with the surface of the cliffs and foreshore, but more usually they are exposed in the bottom of goes or clefts, or stand up as wall-like masses. Some show fine spheroidal weathering.

They are usually very straight, with the edges smooth and parallel, and seem to be intruded along joints in the conglomerate, but occasionally they transgress from one joint plane to another and at such places are usually very irregular, breaking up into two or more portions with included islands of conglomerate and sending out irregular apophyses into the surrounding rock. With the trifling exceptions noted below, they always maintain a general N.N.W. direction. They alter the conglomerate very little; it is baked and hardened for an inch or two from the dyke, but that is all. The dykes themselves usually show beautiful chilled margins of very fine-grained or almost glassy rock for a depth of several inches passing into a quite coarsely crystalline interior.

The largest dyke, sometimes called the "King Dyke," is at Geodha Na Muic, on the south of Druim Mor, and is an impressive object, conspicuous even from Eye on the far side of Broad Bay, four miles off. It stands out from the cliff as a great wall, 21 ft. thick, and also forms the western side of one of the finest goes in the district.

On the shore just E. of the village of Aird Tunga (or Aird of Tong) there is a four feet dyke, traceable for over 300 yards, which curves round from N.N.W. to N. and then N.N.E.

At the west end of Eilean Na Gothail, ("Goat Island") in Stornoway Harbour there is a large compound dyke[2] of many

[1] Morrison (1885, p. 24) records that there is a dyke in Holm, but I have not yet been able to find it.

[2] Olivine-dolerite (crinanite); *c.f.* Stevens (1914, p. 60).

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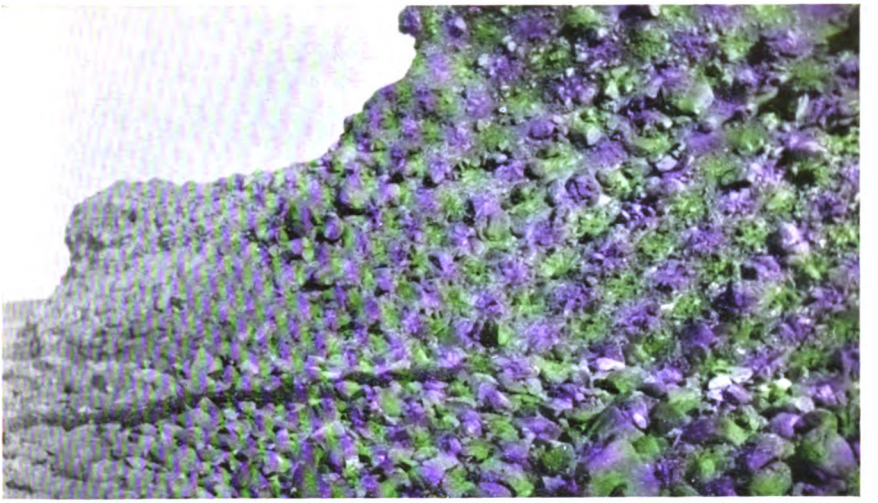

Fig. 1.

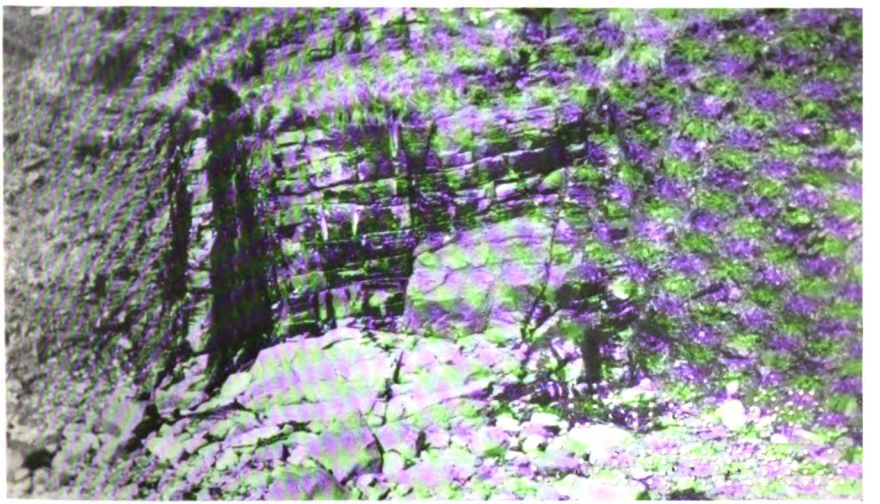

Fig. 2.

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anastomosing branches covering a belt nearly a hundred feet wide, about 30 or 40 feet of which consists of dolerite. Its direction is N.W. Its intersection with one of the ordinary N.N.W. dykes is, unfortunately, just out of sight below low water mark.

On the south side of the Arnish Peninsula at Sgeir Alla there is a pretty example of a little dyke gradually pinching out in the upper part of the cliff until it disappears as a few tiny strings in cracks of the conglomerate. The liquid must have been very fluid and forced in under great pressure.

### 7. The Adjoining Lewisian Gneiss.

I have examined the gneiss for a mile or two back from the faults, and also that in Eye, but have made no effort to map it in detail. The general descriptions in "The Geology of the North West Highlands"[1] seem to apply accurately to the Stornoway gneisses. In this district the main foliation and banding usually dips at very steep angles. There are considerable areas where the dips appear very variable, but over larger areas, sometimes quite two or three miles across, the dip is very constant in direction. For instance, along the south coast of Eye from Swordale to Bayble, a distance (ignoring minor indentations) of four miles, the dip is always between S. and S.E., usually S.S.E., at from 30° to 90°, usually about 45°.

In a belt from one to two miles wide W. of the N.-S. boundary fault through Stornoway Harbour, and extending at least from the Amhuinn a Ghlinne Dhuibh on the north to Tob Leiravay on the south, a distance of nearly five miles, the dip is nearly always E. or E.S.E., again at from 30° to 90°, usually 45°. And this dip may prevail over a considerably larger area. Dips of less than 30° are rare near Stornoway. Detailed mapping will evidently bring out a good deal of the structure.

All the gneisses in this district appear to be of igneous origin. I can find no trace of rocks which suggest metamorphosed sediments resembling the Loch Maree Series. If such rocks exist within a mile or two of the Torridonian boundary they must be very inconspicuous and their outcrops small. Large areas of ground are, however, covered by drift and peat. It may be

[1] *Mem. Geol. Survey*, 1907; see also Peach and Horne, (1913, p. 471 and Stevens (1914, pp. 52-54).

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mentioned here that there are said to be schists in Park, a part of Lewis I have not yet visited, which from the imperfect description may well prove to be of sedimentary origin. On the N.W. coast of Eye, between Garrabost and Shulishader, there is a particularly fine group of basic sills in the Lewisian.

Numerous fine new sections of gneiss in quarries and cuttings have been available near Stornoway during the last few years in connection with the late Lord Leverhulme's roads, especially along the Shore Drive from Lews Castle southwards to the mouth of the Creed River.

### 8. Glacial and Recent.

Most of the interior of central and northern Lewis is so covered with thick drift and peat that the gneiss only occasionally outcrops in glaciated bosses and hummocks, or in unusually deep burn sections. But around the coast there is usually a belt a mile or two wide where there is less drift and the free drainage to the sea has hindered the growth of peat. What peat there was in this coastal region has often been cut away. Here there are often considerable areas of naked gneiss, where the numberless lochans lie in rock-basins, sometimes of perfectly clean and glacially smoothed gneiss. Inland the lochs usually occupy shallow hollows in the drift. Arnish Moor, an area of several square miles S.W. of the policies of Lews Castle, has large areas of bare rock, and in parts presents a really remarkable collection of glacial curiosities: smoothed and rounded gneiss bosses and basins, roches moutonnées, and glaciated pavements with stranded boulders of all sizes are seen on every side in beautifully fresh condition.

The Drift presents the following varieties, the distribution of which I have not worked out:

(*a*) Stony or gravelly Drift, sometimes with thin beds of sand.

(*b*) Boulder Clay of two kinds: (1) bluish or greenish-grey clay, probably derived from Lewisian Gneiss areas, and (2) reddish or pale chocolate coloured clay, probably derived from Torridonian rocks.

All three kinds of drift are very common. The stones in the boulder clay are nearly all Lewisian Gneiss, derived either immediately from that formation or mediately through the Conglomerate. Pieces of red sandstone are very rare. A good deal of the stony and gravelly deposits common in the interior seems to

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represent boulder clay from which most of the clay has been washed.

A number of fine ice-transported boulders and blocks of Lewisian Gneiss were observed. Quite the most remarkable group in the district is on the Allt Na Sniomh, 1200 yards N.E. of the bridge which carries the Stornoway-Barvas road over the Amhuinn a Ghlinne Dhuibh. There are here a number of large boulders, some of them ten feet long, lying in a shallow valley.

Two conspicuous boulders lie, within a few yards of each other, half buried in peat on the Druim Ghreamir, half a mile due E. of the bridge over the Laxdale River on the main road north from Stornoway. The larger is about twelve feet long.

In the Stornoway district there are no traces of the raised beaches and old sea margins so evident on some parts of the Scottish coasts. There is a marked terrace of coarse, loose, gneiss gravel, with its nearly flat top 25 ft. above O.D., on the south side of the Laxdale River at Laxdale, just E. of the main road north from Stornoway. This seems to be a fragment of an eroded fan of gravel washed down from the interior when the river was of a more torrential character than at present. It is probably late glacial.

At the seaward face of one or two of the areas of sand-dune and shingle-bank peat and marsh deposits are exposed on the foreshore, slightly below high water mark and undergoing erosion by the sea, but this seems to be due not to any depression of land, but to the rolling back of the dunes and shingle on to and over the marshes enclosed behind them, where a good deal of peat and alluvium has formed at about sea level.

There are several of these areas of marsh protected by dunes and shingle banks. Sometimes they contain peat, but usually they consist of a laminated deposit of alternate layers of pale, sandy alluvium and dark peaty alluvium, several to the inch. The sand dunes consist almost entirely of comminuted shells, and there seems to be an enormous quantity of shell-sand in the shallow Loch a Tuath or Broad Bay. At the north end of the Stornoway Golf Links, at the Carse of Melbost, there are great banks or dunes of shells, 12 or 15 ft. high, in every stage of breaking down into sand. For nearly a mile along the N.W. coast of Eye, from West Roisnish to Dun Mor, there is an extensive landslip, mainly in the conglomerate but also involving gneiss and drift. The little bay Geodha Rosinish is a very symmetrical amphitheatre of waterlogged slips.

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## II. Note on Some Foliated Granites in Western Lewis.

### 1. Granite Intrusions in Western Lewis.

Near the Atlantic coast of Lewis, in the district around Loch Roag, there are several large and small masses of foliated (*i.e.* sheared) granite in the Lewisian Gneiss complex. Their intrusive character is plain from a number of sections, and they are among the latest of the numerous and complex series of intrusions of the Lewisian formation, for at one place or another they can be seen to cut dykes and sills belonging to all the types usually found in the Lewisian Gneiss, while no dykes were seen to penetrate them. They are conspicuous and distinctive rocks, and I am strongly inclined to the opinion that they are actually the latest of the Lewisian intrusions. They were obviously intruded when the general mass of the gneiss had assumed nearly its present character. They are always foliated, although seldom strongly so, and often the foliation is quite faint and not very obvious in a hand specimen. It is possible that these granites may even be much later than the surrounding rocks, and not pre-Torridonian at all.

### 2. The Carloway Boss.

This boss is at Dalebeg, nearly three miles by road N.E. of Carloway Bridge. It has sometimes been referred to as the Bragor (Morrison, 1903, p. 558) or Dalebeg Granite. Its existence has been known for a long time, for it forms a conspicuous ridge (Ben Guidamol), and the main coast road happens to pass along two sides of it. I was surprised to find how small it is. It forms a roughly oval boss, measuring about 800 yards from N. to S., by nearly 600 yards from E. to W., and hardly approaches within half a mile of the coast. Its highest point is 426 ft. above the sea. The stone for Lews Castle at Stornoway is said to have been taken from here about eighty years ago, and there are old quarries on the N.W. of the boss. The granite, although rather closely jointed, seems to provide an excellent building stone.

The rock is usually a handsome pink granite of medium grain, slightly, but distinctly foliated. The degree of foliation and the coarseness of the granite vary considerably in different parts of the boss. In some places there are distinct augen of felspar. On the summit plateau of Ben Guidamol, in the central part of the granite area, the rock lies in a somewhat flaggy manner, the pseudo-bedding being parallel to the foliation.

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On the west side of the boss the junction with the gneiss is concealed under extensive slopes of granite scree over which the road passes, but round most of the periphery the line can be easily followed, and the junction is exposed at several places. Except at one place, where the boundary seems to be a faulted one, the junction suggests that the granite is intrusive in the gneiss, and at two or three places this is clearly shown to be the case. Although the granite is sometimes seen to send small veins for a few feet into the gneiss, and the junction is usually, when regarded on a small scale, irregular, the boundary on the whole follows a very even and definite line, and I saw no large veins or apophyses given off from the granite. The dyke-like exposure of fine-grained granite on Cnoc Na Cartach, 600 yards from the S.W. margin of the boss, mentioned below, is probably connected with the larger intrusion under-ground.

Wherever the general slope of the granite boundary could be estimated it is steeply inclined, except about the S.E. (*i.e.* on top of the plateau), where the gneiss lies over the granite. Although the number of these observations of the margin was not sufficient for a certain deduction, the intrusion appears to be an oval boss, the upper part of which had something of the general form of the existing steep-sided granite ridge. The upper surface may not have been very much above the present summit plateau.

A few specially interesting points on the granite boundary, which is about a mile and a quarter long, may be briefly noted.

At the N. end of the western scree slopes, at the N.W. side of the granite, where the screes pass into the precipitous N. face of Ben Guidamol and the road makes a right angle turn to the E. above Loch Raoinavat, there is a good section of the edge of the granite in the old quarries by the road, still worked to a small extent for road metal. The boundary is here almost certainly faulted. Its direction is N.E. It is very steep or vertical. The granite first becomes much shattered and then passes into a zone, several feet across, of entirely crushed or mylonised rock of a light pink colour streaked with black. The margin of the gneiss is here formed by one of the grey, fine-grained, nearly unfoliated, basic dykes. The junction is sharp and in places slickensided, with an inch or two of platy mylonite between the basic dyke and the crushed granite. Numerous slickensides are also visible in the crushed granite. The Lewisian dyke is much shattered for two or three feet, but is not so crushed nor nearly so deeply affected as the margin of the granite.



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Eastwards the granite boundary for a while keeps close to the road, but soon diverges from it in a S.E. direction and mounts obliquely up the steep N. face of the hill, and passes over its N.E. shoulder. The junction is well exposed in at least two places on the nearly precipitous hillside, but they are rather difficult of access. Here the granite is clearly intrusive in the gneiss and the boundary is not faulted. It is very steep or vertical. The line can be easily followed along the N.E. slopes of Ben Guidamol, and then up on to the summit plateau. Where exposed the junction seems to be intrusive and steeply inclined, but the sections are not very clear. As the top of the hill is reached, however, the gneiss distinctly tends more and more to lie on top of the granite, which disappears under it at a decreasing angle.

The little triangular Loch Beg Ben Guidamol lies on the plateau in a rock basin at a level of about 390 feet. Its N. and S.E. sides are gneiss, but the western side is granite. At one place near here the gneiss undoubtedlv lies nearly flat on top of the granite, the surface of which passes under it with a gentle E.S.E. dip.

South of the loch there is a good deal of peat, but exposures on each side show that the granite boundary turns westward towards the road. At the S. end of the boss, just where the line passes over the edge of the plateau, and begins to slope obliquely down the hillside in a N.W. direction towards the road (*i.e.* close to where, as one looks up from the road, the granite boundary comes over the sky-line of the ridge), the junction is beautifully exposed in the little cliff at the top of the slope. Here the intrusive nature of the granite is obvious, veins of it penetrating the gneiss and isolating portions of it. The general line of the junction seems again to be very steep or even vertical. Towards the foot of the slope, a little way above the road, the edge of the granite passes under the screes. The Dalebeg Burn in the valley below flows entirely over gneiss.

### 3. The Valtos Boss.

In Uig there is a much larger boss of a similar foliated granite, which I have not yet been able to map. Like the Carloway Granite, it tends to stand up as high ground, and gives rise to cliffs and screes. The pink colour of the rocks also makes it a conspicuous feature. The southern side of the boss is generally (although not entirely) coincident with the remarkable E.-W. cleft of Glen Valtos, through which passes the road from Meavig to Uig. The granite area also includes the fine red hill Nisa

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Mhor (448 ft.), between Meavig and Valtos village. The outcrop of the boss seems to have the form of an irregular oval, with the long axis directed W.S.W. and E.N.E., and nearly two miles long. It does not seem to reach the sea at any point.

The only section I have seen of the junction of the granite with the gneiss is at the E. end of Glen Valtos, on the N. side, a few feet above the road, and close to the road bridge across the burn. Here the junction is sharp and on the whole steeply inclined, but highly irregular, and the granite seems to be clearly intrusive in the gneiss.

The rock is a pink foliated granite, medium to fine in grain. As usual, foliation is far less strongly developed in the granite than in the surrounding gneiss, which was independently foliated to practically its present state before the intrusion of the granite. The Valtos Granite closely resembles the Carloway rock, and there seems no reason to doubt that it is of the same general age.

### 4. Minor Granitic Intrusions.

In addition to the two bosses above mentioned, five smaller granitic intrusions were noticed in the Loch Roag district, and there are doubtless others. These minor intrusions are usually of rather finer grain than the two large bosses, and are sometimes highly foliated, but from the manner in which they cut all the kinds of basic dykes and sills, it is probable that they belong to the same period as the larger masses. They are easily recognised in the field, being pink in colour and usually standing up as ridges and small hills above the surrounding grey gneiss. The following is a list of those noted:

(*a*) A narrow E.-W. dyke-like intrusion, of fine grain and highly sheared, on Cnoc Na Cartach, 600 yards from the S.W. edge of the Carloway granite boss. It is about 200 yards long.

(*b*) A considerably larger mass just N.E. of Tolstachoelish village, on both sides of the main road, near milestone 4 from Callanish. It is about a third of a mile long from S.W. to N.E., by from 150 to 200 yards across. It is of fine grain and well foliated.

(*c*) There are three small bosses of granite in Breasclete village. They are of rather coarser grain than the two intrusions last mentioned, and within the bosses there are places where the rock is almost unfoliated. Near the margins the foliation is always distinct. Two of the masses form small but conspicuous

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hills: all are of roughly oval form, and the two largest each measure nearly 250 yards over the longest diameter. The junctions with the gneiss are usually steep.

### 5. The Lewisian Gneiss around Loch Roag, and its Faults.

The country rock of the district is gneiss of the usual Lewisian type, but there is an unusually varied suite of dykes and sills, mainly basic, including a number of exceptional character,[1] especially around the villages of Breasclete and Callanish. Some of the dark basic dykes are almost unfoliated, and their intrusive character is beautifully clear. A few which have the appearance of almost unaltered basalts or dolerites, and sometimes show marked spheroidal weathering, may even be Tertiary dykes. There is a fine example of this type, weathered into many-layered rounded lumps, in the west bank of the Carloway-Stornoway road, one third of a mile E.S.E. of Carloway Bridge. It strikes nearly north and south.

It has sometimes been stated that there is a small outlier of Torridonian rocks near Dun Carloway.[2] No such rock seems to exist anywhere near that place, nor, so far as I have yet seen, anywhere in western Lewis. In view of the interest which would attach to a Torridonian outlier in so westerly a situation, I made a careful search for it. The rock exposures are numerous and admirable, but no trace of Torridonian was seen.

The main structural lines of the district run N.N.W., or nearly N.-S. The chief faults, crush-zones, and basic dykes of the Lewisian Gneiss all have this trend, which is naturally that of most of the valleys, of the lochs which they contain, and of the streams and roads which traverse them. This tendency to N.N.W. lines is very obvious on a map when contours, streams and roads are taken into account

There is a second but less prominent system of east and west lines crossing and apparently shifting that above mentioned This is exemplified in Loch Carloway, the straits N. and S. of of Great Bernera, and in the cleft of Glen Valtos. It may be recalled that in the Stornoway district, on the other side of Lewis, the system of faults in the Torridonian outlier in that region also runs nearly N. -S., and nearly E.-W.

[1] Flinty crush-rocks also occur.

[2] Macculloch (1819); Morrison (1885).

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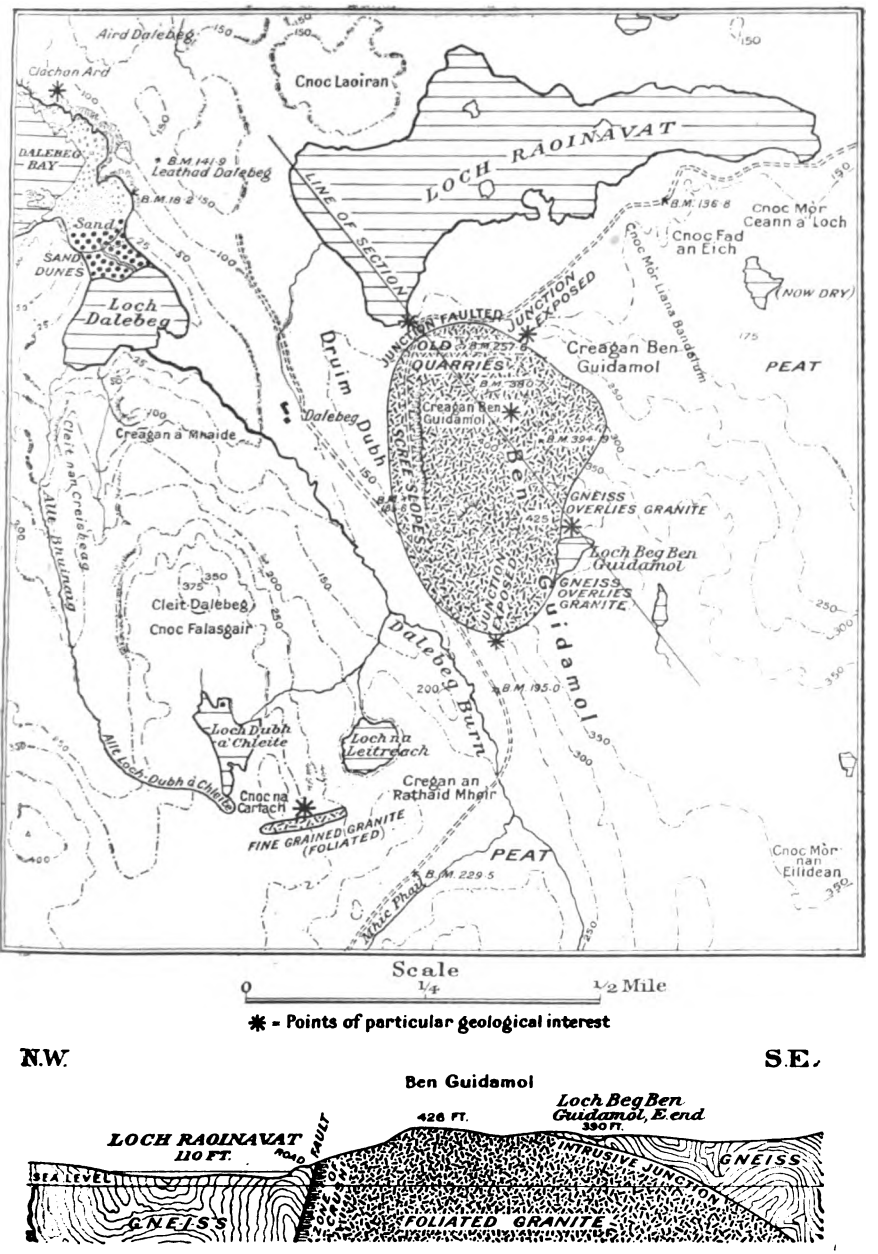





**Fig. 25.** SKETCH-MAP AND SECTION OF THE CARLOWAY OR DALEBEG GRANITE BOSS.

The area left white on the map is Lewisian Gneiss

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Around Loch Roag the gneiss is greatly broken up by N.N.W. faults and crush zones, which often run nearly straight for considerable distances. The faults are frequently marked by lines of cliff or steep scarps on what is probably the upthrow side. These straight lines of inland cliffs are a feature of the district and their appearance suggests that there may have been movement along them in comparatively recent geological periods. They are occasionally over 100 ft. high and nearly vertical, and cliffs of 40 or 50 ft. are numerous. The peninsula on the N. side of Loch Carloway, with the little lighthouse on its western point, particularly exemplifies this structure; the whole of it is cut into a series of slices by N.N.W. faults crossing it. Several successive lines of cliff have to be climbed up and down before the lighthouse can be reached. There is here a beautiful little example of a valley due to trough-faulting, the valley W. of Ben Borroswton being bounded on both sides by straight lines of steep cliffs which are almost certainly fault-scarps. The fault which gives rise to the cliff along the E. side of the main road at Dun Carloway can be traced from Loch Carloway, where it seems to be cut off by an E.-W. fault along the Loch, southward through Dun Carloway and Tolstachoelish to the E. shore of Loch Roag, a distance of 4 miles. These inland cliffs, especially that along the fault just mentioned, often show beautiful sections of the contortions and recumbent folds of the gneisses. The sections opposite Dun Schoolhouse may be specially mentioned.

### 6. Glacial and Recent.

The interior is heavily mantled with drift and peat, but a belt two or three miles wide around the coast shows much bare glaciated rock, and Ben Bragor (857 ft.), is the chief feature of a fine group of hills of nearly naked grey gneiss. The glacial phenomena are very fine. Any traveller along the road from Callanish to Carloway must be struck by the rows of transported blocks of gneiss on the glaciated slopes to the east of the road and perched conspicuously on the skyline. Roches moutonnées abound. The region about the junction of Little Loch Roag with West Loch Roag presents beautiful examples of smooth shores of glaciated gneiss and bare rounded islets sloping steeply into the water. In these sheltered upper reaches of the great loch the sea has as yet eroded the glaciated surfaces very little

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and there are only discoloured marks to show where the tide rises and falls against the smooth rock slopes.

No evidence could be seen as to changes of level. Raised beaches and terraces are absent both on the open coast and along the shores of Loch Roag.

It may be mentioned here that in the Ness district at the Butt of Lewis the drift contains numerous pebbles and small boulders of undoubted red Torridon Sandstone, usually of Applecross type. These sandstone pebbles are often nearly as numerous as those of Lewisian Gneiss. Torridon Sandstone is rare in the drift over most of Lewis, and its abundance at the Butt suggests that there may be Torridonian rocks *in situ* at no great distance, perhaps beneath the water of the Minch.

As on the E. coast about Stornoway, there are several large areas on the Atlantic of blown shell-sand in dunes, often enclosing areas of lagoon and alluvial marsh behind them. The ocean is shallow for some distance off the coast, and seems to contain great quantities of this sand. The largest areas of dune and marsh are at Barvas, Arnol, Valtos, and Camus Uig. At Barvas the dunes extend along the coast for two miles, and the belt is often over half a mile wide. In places the sand has been carried some way up the slopes of the hills and lies on the gneiss at a height of over a hundred feet. Loch More Barvas, over three quarters of a mile long, is the largest of the lagoons. Loch Arnol and its alluvial marshes extend nearly a mile inland behind the dunes.

Lewis is now treeless, but remains of small trees are of frequent occurrence in the peat.

It may be mentioned that the well known groups of standing stones at and near Callanish village (the great group with 48 stones still standing, and four smaller circles in the neighbourhood), all consist without exception of slabs of the local coarse, flaggy, acid gneiss. There is no stone which could not have been obtained within a few yards of where it stands. The largest slab stands 17 ft. out of the ground. The slabs seem, in some cases at any rate, to have been split out by means of fire, in the manner still extensively employed in quarrying exactly similar rocks in the State of Mysore.

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## III. The Stromness Granite-Gneiss Inliers and The Surrounding Rocks.

### 1. The Granite-Gneiss.

(*a*) Introductory. The area covered by these notes includes the Parish of Stromness, the southern half of the Parish of Sandwick, and parts of the Parishes of Stenness and of Hoy and Græmsay. There here occur four inliers of granite and gneiss outcropping as "islands" in the surrounding Middle Old Red Sandstone flagstones. The waterworn surface of the ancient rocks where they pass under the Middle O.R.S., and the marginal deposits of breccia, conglomerate, and false-bedded sandstone (obviously once cliff-screes, beaches, and sand-banks) which usually fringe them, show that they once actually were a group of rocky islands in the Old Red Lake (Lake Orcadie). Other outcrops of the highly irregular floor on which the Middle O.R.S was deposited occur in Caithness at Loch More, Caplaich Hill, and Dirlot. (*See* "Geology of Caithness," *Mem. Geol. Survey*, 1914, pages 18 and 62).

(*b*) The Græmsay Inlier. This occupies the N.W. portion of the Island of Græmsay. A part of it is under the water of Hoy Sound, but from the direction of the boundary at the two points where it passes out to sea, and from the fact that the reefs called the Lash, at the mouth of the Bay of Sandside, and the Skerry of Cletts, in Hoy Sound, consists of flagstone it seems probable that the area of gneiss under the Sound is not very extensive; that the inlier has the general form of an oval with the long axis directed N.W.-S.E.; and that it is somewhat less than a mile long, by about 700 yards wide. Inland the exact position of the boundary is not very clear, but the crystalline rocks reach a height of well over 100 ft. on the hillside above Clettabreck, and there are two particularly conspicuous bare outcrops known as the Face of Cletts and the Hillock of Fulzegeo. The rocks, however, are best studied along the fine coast section, extending nearly 1500 yards from the W. side of the Bay of Sandside to the Lighthouse on the N.W. point of the island. This is the longest and best section of the crystalline rocks in the Stromness district. For most of its length the rock is unusually thoroughly foliated and is typical gneiss rather than a foliated granite. The foliation usually dips W. or S.W. at steep angles. The complex veining with fine-grained granite, pegmatites, and

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white quartz is also well displayed. The eastern margin of the inlier, seen on the W. side of the Bay of Sandside, is steeply inclined and may be faulted, for the rocks here are somewhat disturbed. The general view of this inlier from the Ness, on the other side of Hoy Sound, three-quarters of a mile away, brings out admirably the general contrast between an area and coast line of the crystalline rocks and the forms displayed by the flagstones.

(*c*) The Stromness Inlier. This is much the largest of the inliers and is of irregular form. It is over two miles long from N. to S., and for most of its length 1400 or 1500 yards wide, but there is in addition an area of granite N. and N.E. of Stromness Reservoir which is only joined to the main inlier by a narrow neck 250 or 300 yards wide. The town of Stromness stands on this granite, and most of Stromness Harbour lies in a hollow in it. Its central portion is occupied by the fine granite hill Brinkie's Brae (311 ft.), rising immediately behind the town, on the upper part of which there is a good deal of bare granite and several quarries. At its N.W. corner the inlier rises to well over 400 feet on the Hill of Lynedardy, although the boundary of the granite is here somewhat uncertain. Near the southern end of the inlier is the conspicuous little granite kopje, with an old cannon on it, called "The Citadel." There are good exposures of the rock on the shore of the Harbour at the south end of the town, and on the shore of Hoy Sound at the Ness, where the southern extremity of the granite seems to occur just below low water mark, for the Skerry of Ness off the shore consists of flagstones.

(*d*) The Stany Knowe Inlier. The second pair of inliers occur two miles N.N.W. of the northern edge of the Stromness granite. The space between is occupied by hills of normal flagstone. Stany Knowe is a very conspicuous kopje, with a great deal of bare granite, 340 ft. high and forming the western half of a somewhat hourglass-shaped inlier, the long axis of which extends W.N.W. and E.S.E., and is nearly 1200 yards long. The eastern end rises nearly to the 400 ft. contour on the western slope of Cringla Fiold. In this eastern half of the inlier there are good exposures of the crystalline rocks in the Face of Scarra, and in the burn section along the Burn of Sowadee, which crosses the entire inlier (here nearly 400 yards wide), from S. to N.

(*e*) The Inganess Inlier. This lies immediately to the W.N.W. of that last mentioned, and is only separated from it by a thin sheet of conglomerate and flagstones, 200 or 250 yards wide, over

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Crua Breck, the N.W. shoulder of Stany Knowe. The crystalline rocks slope down to the W. coast at Inganess and also form the south side of Garthna Geo, the bay on the north side of Inganess, and there is a fine coast section of the rocks nearly half a mile long, so that a portion, although probably the lesser portion, of this inlier is under the sea. The visible part has the form of a trapezium with rounded angles, and the longest line across it measures about half a mile. The reefs called Whyabatten, exposed at low water in the entrance to Garthna Geo, look as if they consisted of the granite, but of this I am uncertain, as I could not reach them, and, as usual in Orkney with rocks below highwater-mark, there is such a luxuriant mantle of seaweeds that the rock is quite concealed. The cliff section is interesting, although not easy of access; the junction of the granite with the sediments (here highly false-bedded grit and sandstone) is seen at the inner angle of Garthna Geo and is nearly vertical. Unless the junction is faulted (of which there is some suggestion), the sandstone here rests against a granite cliff of the O.R.S. period.

In addition to these four inliers, a small outcrop of conglomerate of stones of gneiss and granite, identical in character with the deposit which usually fringes the crystalline rocks, occurs in the flagstones on the southern slope of Erne Toog, just over a mile W.N.W.of the Steamer Pier at Stromness, and suggests that the older rocks are here close to the surface. This exposure is seen in the track half way between the houses of Hillhead and Heatherybraes on the W. side of the hollow called Hediscope.

(*f*) Character of the Rocks.[1] The boundary of these inliers of crystalline rocks makes as a rule no feature at the surface, but the granite-gneiss often tends to stand up as high ground and to produce conspicuous rocky kopjes. The rocks of all four inliers are very complex when taken in detail, but have a similar general character. All appear to be exposures of a single large complex of acid plutonic igneous rocks in a more or less metamorphic condition. The prevailing rock is a granite, usually pink but sometimes grey, and varying in grain from medium to quite coarse. There are sometimes conspicuous nests of large felspar crystals. Over considerable areas (*e.g.* over much of Brinkie's Brae behind Stromness), it is nearly or quite unfoliated, but more usually it is distinctly foliated by a parallel arrangement of the crystals. This foliated granite passes in many places into typical gneisses

[1] *cf.* Heddle (1879, p. 135); Flett (1898, p. 391).

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where the constituent minerals are sorted out into folia of differing composition. These various degrees of coarseness and foliation pass quite gradually into each other, and seem to be of irregular distribution, although the same general condition is usually maintaimed over areas of many acres. Within the inliers it was not found possible to draw any boundaries separating definitely different kinds of rock. I have several times called this groundmass of the inliers by the title of " the granite-gneiss " as I know of no single word for a rock which is sometimes a granite, sometimes a foliated granite, and sometimes a true gneiss.

The rock just described is veined in a minute and complex manner so that it is unusual for an exposure of more than a few square feet to be seen without a vein of some kind entering into it. The veins vary from mere strings up to a width of several feet. They are frequently very irregular and anastomose in a complicated manner. The junctions with the granite and gneiss into which they were intruded or in the cracks of which they were deposited are usually quite sharp. A vein can usually be referred to one of three kinds:

(1) Veins of fine-grained pink granite usually nearly or quite unfoliated. These are conspicuous in the coarser granite especially when it happens to be grey in colour.

(2) Pink or flesh-coloured Pegmatites. Old accounts of the inliers probably include these two classes together as " veins of Felsite."

(3) Veins of white quartz, often very contorted.

The whole complex seems to be of igneous origin. With the single possible exception here mentioned, no gneisses or schists which suggest altered sediments were seen, but there are many exposures which I have not examined in detail. In the coast section of the eastern margin of the Graemsay inlier on the W. side of the Bay of Sandside there are some small exposures of a grey schist or fine-grained gneiss which may prove to be of sedimentary origin.

As regards the correlation of these crystalline rocks, they are certainly not Lewisian gneisses. There seems no reason to doubt that what is seen is part of another of those complexes of acid igneous rocks several of which occur in the northern Highlands, and are there seen to be intrusive in the sediments of the Moine Series. As much of the Stromness rock is well foliated and often

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passes into true gneiss, it is suggested that the complex belongs to the older of the periods of these intrusions.

2. The Marginal Deposits around the Granite Inliers.[1]

(*a*) General Description. The granite inliers are surrounded by an interesting suite of marginal deposits derived from their own debris and forming a local base to the flagstones. These deposits are very variable both in space and time; sometimes almost normal flags extend right up to the granite and lie quietly against its water-worn surface, but usually beds of coarser sediment begin to appear as the granite is approached, and in contact with the crystalline rocks there is usually a conglomerate or breccia of varying thickness. The various kinds of marginal sediments pass into each other, but the following general types can be distinguished.

(1) A closely packed conglomerate or breccia of stones of granite or gneiss lying in contact with each other in a scanty matrix of sandstone or sandy flagstones. Sometimes the deposit is a conglomerate of fairly well rounded pebbles; occasionally a breccia of almost sharply angular fragments; usually it consists of sub-angular stones. The fragments lie tumultuously and are of all sizes up to 8 or 10 in. long. At one or two places many blocks up to 12 or 18 in. long are seen, and the rock is best described as a boulder-bed. Where this close conglomerate is seen resting on the irregular, water-worn surface of the granite and filling up clefts and hollows in it (as on the S. side of the Ness, S. of Stromness) it is a little difficult at first sight to determine where the granite *in situ* actually begins.

(2) A much more open breccia or conglomerate in which the sub-angular fragments of granite lie some way apart in the sandy flagstone, or even appear only in lines or thin layers, scattered wide apart in almost normal beds of flagstone: *e.g.* the large roadside quarry on the main Stromness-Kirkwall road near the farm of Burnside, 800 yards N.N.E. of the Market Stance at the N. end of Stromness.

(3) A very fine breccia of granite fragments, passing into a grit. This type, alternating with beds of sandy flagstone, is well seen on the S. side of the Ness, S. of Stromness, just to the W. of the outcrop of granite.

[1] *cf.* Murchison (1859, p. 411); A. Geikie (1879, p. 410); Flett (1898, p. 391).

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**Fig. 26. GEOLOGICAL SKETCH-MAP OF STROMNESS DISTRICT.**

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(4) Highly false-bedded grey sandstone. A fine section of this rock is seen in the cliff on the inner side of Garthna Geo and in the curious perforated stack called Yeskenaby Castle just off it.

(5) Beds of sandy or nearly normal flagstone, evenly bedded.

Making an appropriate allowance at each section for the westward tilting which the area of the granite inliers has undergone, It is plain that the marginal deposits were laid down against irregular rocky shores of very various inclination; sometimes against a gently shelving shore; occasionally against steep slopes approaching the character of cliffs. As the flagstones in the neighbourhood frequently display ripple-marks and even sun-cracks, the Old Red lake around the granite outcrops was obviously sometimes shallow, and the inliers must have stood up as a group of rocky islands, partially surrounded by banks of more or less water-worn debris and screes, approaching the character of beaches, and by shifting sandbanks. These false-bedded sands and the worn character of the granite surface and of the stones in the conglomerate suggest that the water was not always or everywhere placid, or perhaps even very shallow, and that strong currents flowed at times about the islands. From the plant remains in the flags it is probable that the land, and perhaps silty shallows beside it, supported some growth of *Psilophyton* and related plants.

Owing to the irregular manner in which the beds and deposits of coarser sediments occur in the flagstones around the inliers their thickness cannot be measured in the ordinary manner where it is thickest, however, there must be 40 or 50 ft. of nearly continuous conglomerate, measuring perpendicularly from the surface of the granite. Even where there is not much conglomerate or sandstone they may make a considerable show where the granite surface passes underground at a very gentle angle. At places, as noted above, there are no distinctive marginal deposits. On the other hand, at the quarry on the Kirkwall road, 800 yards N.N.E. of Stromness Market Stance, and in the Mill Burn N.W. of the quarry, bands of open breccia occur in the flags 200 or 250 yards from the edge of the granite. In Garthna Geo normal flags do not set in for over 300 yards from the steep edge of the granite, and the cliff section shows that there is a great mass of false-bedded sandstone here. As the marginal deposits often die away gradually into the flags horizontally and are apt

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to alternate vertically with beds of normal flagstone, it will be understood that where a line is drawn to show their outer termination its position is necessarily somewhat arbitrary. With the exception of the little inlier of conglomerate on the slope of Erne Toog, mentioned in a previous paragraph, no fragment of granite or of any other rock was seen in the flags more than 200 or 300 yards from the edge of the granite.

(*b*) Some Local Details. (1) The Graemsay Inlier. The marginal deposits of this inlier consist mainly of a nearly continuous covering of conglomerate of very varying thickness. There seems to be little grit or sandstone. At the coast section on the W. side of the Bay of Sandside the conglomerate is very thin, but as noted above, the boundary is disturbed here and may be faulted. The other coast section, however, around the N.W. Lighthouse is one of the finest exposures of the conglomerate in the district. It is here unusually thick and occupies a broad belt of the reefs and low cliff. At its outer edge it passes rather rapidly into normal flagstones.

(2) The Stromness Inlier. On the greater part of the N.E. and E. side of this inlier and around its southern extremity at the Ness there is a considerable thickness of conglomerate with subsidiary bands of grit and sandstone in the flagstones at its outer margin. Exposures on the foreshore on the N. side of the Ness under the Ness Shipbuilding Yard and the old Fish-curing Station, however, show that conglomerate is at that place nearly or quite absent. On the E. shore of the Harbour just N. of the ruins of Whitehouse, and also at the S. side of the Ness just W. of the granite, the conglomerate is very coarse and passes into a boulder-bed.

The marginal deposits are well seen on the S. side of the Ness; on the W. side of Inner Holm and on the N. shore of the little strait separating it from Mainland; along the E. side of the Harbour and Hamla Voe at its head; in the quarry on the Kirkwall road previously mentioned; along the Mill Burn between the Mill of Cairston and the Mill Pond; and behind the fish-manure works and at the mill at Stairwaidy. The section on the S. side of the Ness is one of the best in the district; in passing along the foreshore over the 200 yards of rocks immediately west of the granite outcrop nearly every variety and combination of the marginal deposits can be studied. Along most of the eastern side of the Stromness inlier the surface of the granite seems to pass under

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the overlying conglomerate with a very gentle easterly slope (originally, of course, somewhat steeper as the area has been tilted westward). This causes the marginal deposits to make a considerable show at the surface.

On the west side of the inlier and round its north end conglomerate is thin or absent, and the flagstones at places rest directly on the granite; usually, however, there is a foot or two of rather fine breccia or conglomerate. N.W. of the Reservoir and on the Hill of Lynedardy there seems to be some development of sandstone. The tongue of sediment projecting on to the granite on the west side of the Loan and around Gleanfield consists of normal flagstones, rather thin-bedded and sandy near the margins. On the Burn of Hellia, 200 yards below, and E. of, its efflux from the Reservoir, and in the track just E. of Weaverhall Cottage a thin layer of conglomerate can be seen upon the granite.

(3) The Stany Knowe Inlier. The marginal deposits are not well exposed, but a few feet of conglomerate are visible at each of the two sections of the granite boundary in the Burn of Sowadee, and from the fragments and blocks of breccia and conglomerate which are strewn on the west slope of Cringla Fiold and on Thunder Breck it is plain that the granite which occupies the lower part of the hillside has a fairly thick bed of the breccia resting upon it. Further N. much false-bedded sandstone is seen. Along the N. side of the inlier the position of the belt of marginal deposits is covered by the long narrow bog called Langa Dee, but round the W. end of the granite on Crua Breck there are exposures of a bed of breccia, often only about a foot thick, lying between the granite and the thin sheet of thin-bedded sandy flagstones which lie over the shoulder of the hill and separate the Stany Knowe Granite from that at Inganess. On the south side of the inlier, on the north slope of Scarra, numerous fragments of false-bedded sandstone show that there is a considerable development of that rock. Breccia or conglomerate seems to be very thin or absent here.

(4) The Inganess Inlier. The only inland exposures of the marginal deposits of this inlier which are at all clear are those on Crua Breck, the N.W. shoulder of Stany Knowe, where they are identical in character with those 200 or 300 yards higher up the slope at the W. end of the Stany Knowe Granite. The very thin breccia, with thin-bedded sandy flags above, here lies almost flat on the granite surface which dips gently W. at nearly the same angle as the sediments.

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The coast sections on the S. and N. sides of Inganess are extensive, and show on both sides a great development of false-bedded grey grit and sandstone. On the south side, from the Geo of Inganess to Harra Ebb, there are also thick beds of conglomerate. Beginning at the S. end of the section in the Geo of Inganess, the cliff on the N. side of the Geo is mainly normal flagstones, but the sloping base is a thick bed of breccia-conglomerate, and the granite, which outcrops on the hillside above, probably lies not many feet below. Farther N.W., the cliff gradually comes to consist of false-bedded sandstone, with thick beds of conglomerate mainly in its lower part. At Kaellan Hellier there is a striking local unconformity in the upper part of the cliff. At Harra Ebb the thick beds of conglomerate at the local base are well displayed in the low cliff and wide foreshore, resting on the worn and irregular surface of the granite.

On the N. side of the inlier the inner cliff of Garthna Geo gives a fine section nearly at right angles through a thick zone of very false-bedded grit and sandstone, 300 yards broad. At the Point of Qui Ayre on the N. side of the Geo the sandstone passes gradually into normal, evenly bedded flagstones. In this transition zone is the large Yeskenaby Millstone Quarry, now nearly deserted, which in the 18th and 19th centuries supplied querns and millstones to most of Orkney. On the whole there is considerably more sandstone round these two northern inliers than around the more southerly outcrops at Stromness and Greamsay.

### 3. The Middle Old Red Sandstone Flagstones (Stromness or Achanarras Beds): Their Structure and Thickness.

The solid rocks of the whole area, outside the granite outcrops and the narrow belts of marginal deposits around them, are flagstones of very uniform character. Nearly the whole thickness seen seems to belong to the Stromness or Achanarras Beds or to the upper part of the "Passage Bed Group" of Caithness. The description of the general character of the Caithness rocks given in the Geological Survey Memoir on "The Geology of Caithness" (1914) seems to apply closely to the exposures around Stromness.

The flags are usually grey or blue-grey in colour and often weather buff or orange. Sandy beds, except at the local base, are absent or very rare. Worm-castings, sun-cracks, and ripple-marks, all both large and small, abound, but the only marked



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variation from the uniform fine grain and even bedding of the flags is found in a few places where there are thin beds of a nodular or concretionary character. The nodules consist of impure chert. The flags are usually distinctly calcareous, and some of the darker beds highly bituminous. Occasionally some unusually thick and hard bed forms the back bone of a conspicuous reef along the coast.

The tectonic structure of the district is in main outline simple. There are numerous small rucks, folds, and even faults and lines of crush in the flagstones, involving steep dips for a few yards, often rapidly reversed. Some of the faults are accompanied by a narrow band of fault-breccia, which sometimes contains a little galena. In the 18th century a lead mine was worked for some years at the N. end of Warebeth Sands on the line of one of these small faults and the adit still exists. Fragments of the ore can sometimes be found about the slag-heap at the site of the smelting-house on the top of the low cliff. Each individual disturbance seems, however, to be of small extent and quite local, and over large areas the rocks are quite undisturbed. Except close to their margins (*i.e.* the areas of conglomerate and breccia, and false-bedded grits and sandstones extending at most 300 yards from the granite), the presence of the granite-gneiss inliers has no effect on the flagstones or the local tectonics. The dips in the flags remain constant in direction all round the inliers.

The general strike of the flagstones, and of their folds and faults, is nearly N.-S., or N.N.W.-S.S.E., throughout the area. Six small strike-faults were noticed on the S. coast of Mainland between Breckness and Bu Point, and two in Graemsay, one in the Bay of Sandside and one on the W. coast of the island. They are little more than fractures at the crests of sharp rucks, and none seemed to have a throw of more than a few feet.

Tectonically the area can be divided into a western half and an eastern half.

(*a*) In the western portion (which includes the granite inliers), the flagstones dip steadily to the W. or W.S.W., at moderate angles of from 5°, to 30°, usually about 15°. On the W. coast of Mainland the dip is, therefore, nearly towards the sea. The area which has been thus tilted westwards includes the western hill district, the immediate surroundings of the town of Stromness, all Graemsay except its E. coast, and the N. end of Hoy.

(*b*) In the eastern half of the district, which corresponds roughly to the floor of the central valley of Mainland, on which

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lie the great lochs of Stenness and Harray, and includes the eastern coast of Graemsay and the coasts of the Bay of Ireland, the rocks lie in the main nearly horizontally, rolling at angles, first in one direction and then in the opposite, with occasional small, sharp rucks. The strike is still nearly N.-S. These rocks with their local bends and disturbances can be admirably studied on the E. coast of Graemsay, and on the W. side of the Bay of Ireland, where there are beautiful sections of small arches and troughs in the flags.

As regards the thickness of flagstones exposed in the Stromness district, 300 or 400 ft., is probably an ample thickness to include all the small folds exposed in the eastern half of the area, where the rocks in general lie nearly horizontally and the hills seldom exceed a height of 200 ft. But towards the W. where a steady westerly or W.S.W. dip sets in, the thickness exposed is very considerable. The belt of ground over which this dip is seen to prevail is three miles wide at the southern edge of the map and quite two miles wide in the N. The total effect of the small strike-faults and rucks is probably not great in reducing the apparent thickness, for the throw seems to be as often in one direction as in the other. Taking the average dip as 12° (it is probably slightly more), there are about 3,900 ft. of flagstones exposed in the southern part of the area, where the dips also tend to be steeper than further N. Altogether there may well be over 4,000 ft. of M.O.R.S flagstones exposed in the Stromness district without any sign of the top or bottom of the series, for the coarse sediments around the granite inliers are a purely local base of no general significance, being merely the beaches, banks, and debris surrounding a group of rocky islands in the Old Red Lake, much as the Dolomitic Conglomerate is a local facies of the Keuper Marls surrounding the Mendip Hills.

The highest flagstones exposed in this map are probably at Muckle Head in Hoy on the southern margin. The highest beds in this portion of Mainland seem to be at Braga off Breck Ness. The beds in the central valley are probably somewhat older and lower in the series than any of the breccias and grits exposed at the local base around the granite inliers.

Nearly the whole of the 4,000 ft. of flagstones seems, so far as one can judge from the fossils, which are not everywhere abundant, to belong to the Stromness or Achanarras Beds, or to the upper part of the " Passage Bed Group," well up in the M.O.R.S. of

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Caithness. The Stromness Beds are supposed to be the oldest Old Red rocks seen in Orkney,[1] so the strata exposed about the Loch of Stenness are probably the lowest flagstones to be seen in the islands. It is quite likely that the flags at the N. end of Hoy, and at Braga and Breck Ness on Mainland may belong to the overlying Thurso Group but this, so far as I know, has yet to be proved.

Fossils (as usual almost exclusively fish and plants) are of very irregular distribution. They are scattered but sparsely through much the greater part of the flagstones, and many exposures seem quite barren, but an occasional fish scale or a coccosteus plate, or a reed-like plant may usually be found after a search at most places. But there are some quarries and roadside pits where fossils are very numerous, and at a few of these it is nearly impossible to spilt a piece of flagstone without finding each plane crowded with fish bones, scales, and plates. Entire and well preserved fish are not uncommon at these places.

The following is a list of the best fossil localities observed, but I have no doubt that there are others as good:

(1) A roadside quarry on the E. side of the road which runs N.W. from the Stones of Stenness up the middle of the Ness of Brodgar, and half a mile due N. of the farm of Lyking. Fish extraordinarily numerous.

(2) A large quarry on the opposite side of the same road, and 300 yards N.W. of the quarry just mentioned.

(3) A large quarry on the W. side of the Stromness-Birsay main road, 200 yards N. of the farm of Windbreck, and 4½ miles from Stromness by road.

(4) A small roadside quarry, just opposite Wester Voy Farm, 4 miles N. of Stromness.

(5) The large quarry in the Dale, a quarter of a mile S.W. of Stromness Reservoir, 1½ miles from Stromness.

As usual there are only a few species of fish, but the individuals are sometimes very numerous, so that Lake Orcadie must have often abounded with fish and with food for them. The plant fossils are by no means so common as the fish; still they are not very rare and I suggest that interesting results await a systematic collection and examination of them. Some are plainly Equiseta and Lycopods, but there are some long smooth impressions without nodes, resembling leaves of grass.

[1] *C.f.* Flett (1898, p. 395.)

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### 4. Lava Flow at Navershaw.

At Quoyelsh, the S.W. point of the Bay of Navershaw and two-thirds of a mile E.S.E. of the Steamer Pier at Stromness, there is an exposure of a contemporary flow of light coloured lava (rhyolite or quartz-felsite) in the flagstones. The lava seems to be about seven or eight feet thick, and flow-structure is strongly developed in it. The flow and the rocks immediatley above it are excellently displayed in the conspicuous little point and the foreshore around it, although there is, as usual an annoying quantity of seaweed between the tide marks. The under surface of the lava is not very clearly seen, but the upper surface is extremely broken, uneven and cracked. On the lava lies a bed of a curious breccia, 4 or 5 ft. thick, consisting of sharply angular fragments and splinters of the hard lava lying in a matrix of rather dark flagstone. It is a very conspicuous rock, owing to the colour contrast between the light lava and the darker flagstone. The pieces of lava are of all sizes from nearly a foot long downwards, and are arranged tumultously in the matrix, sometimes as much as two or three inches apart. There is a tendency, however, for elongate fragments to lie parallel to the bedding. The breccia is bedded irregularly, in contrast to the even bedding of the flagstones. At its upper surface it passes rather rapidly, by means of a thin transition bed with small fragments of lava, into the normal flags. That we are here dealing with a contemporary flow is shown by the fact that the flagstone matrix of the breccia descends into and fills up the open cracks and hollows on the uneven surface of the lava, and is quite unbaked and unaltered in that position. The breccia above this lava is a puzzling rock, and I can offer no theory as to its mode of formation.

### 5. Dykes in the Flagstones.

Seven nearly vertical basic dykes[1] were observed along the coast, four on Mainland and three near the N.W. angle of Graemsay They are from 3 to 5 ft. in width, and seem to have been intruded along joints. Occasionally they transgress from one joint to another, but upon the whole they are very straight and regular. They bake the flags for an inch or two, and themselves have extensive chilled margins. They sometimes stand up as wall-like masses across the flagstone foreshore.

[1] Four of these have been sliced and proved to be camptonites as described by Flett (1899, p. 865).

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The two dykes in the Bight of Mousland are exposed in the brow of the cliff a few yards apart, and just N. of the mouth of the Burn of Selta. The conspicuous dyke across the foreshore at the Noust of Nethertown is in line with that near Quoyelsh on the N. shore of Cairston Roads, 1½ miles to the E.N.E., on the other side of the Stromness Granite. The three dykes S. of the West Lighthouse on Graemsay are an exceptionally fine group, beautifully exposed across the wide foreshore.

As regards the direction of these basic dykes, the five more northerly all run W.S.W. and E.N.E., but the two more southerly dykes on Graemsay are nearly E.-W. All appear to be identical in composition, and probably belong to the same general age. The appearance of the Stromness dykes suggests that they are considerably later than the M.O.R.S. flagstones in which they stand, for the flags seem to have been consolidated and jointed in practically their present state when the dykes were intruded.

## 6. Glacial and Recent.

The Stromness district presents all the characteristic land forms and drift deposits of a well glaciated region, but little of special interest was observed. In the western hill range along the Atlantic coast there is usually little drift, except in the valley bottoms, and much of this is of a stony and gravelly character; but on the gently undulating floor of the central valley of Mainland there are some extensive areas of boulder-clay. The stones in the drift (except near the granite outcrops), are nearly all angular or subangular pieces of flagstone. Foreign rocks are rare, although a few pieces of red sandstone, presumably from the John o' Groat's Beds or U.O.R.S., were seen. No very large transported blocks were observed in this area, but small boulders up to three feet long are numerous. All those seen consist of flagstone or the granite gneiss.

The direction of the main ice flow is indicated by the fact that while to the E. of the main outcrop of granite about the town of Stromness there are few or no granite or gneiss stones in the drift, the area to the N.W. of it is strewn with them in such profusion that, in the absence of any good section, it is hard to tell where the real boundary of the granite is.[1] Near the granite there are many more pieces of it in the drift than pieces of flagstone, and

[1] *cf.* Peach and Horne (1880 (2), p. 658).

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granite fragments continue common as far as the W. coast. The ice seems, therefore, to have come from the S.E.

No terraces or raised beaches were observed in the district. The last movement was a slight depression, as indicated by the well known submerged forest in the Bay of Skaill, just to the north.[1]

Most of the western hill range is covered with hill-peat of no great thickness, but several of the valleys among the hills and a number of shallow hollows on the floor of the central valley contain peat bogs and deposits of valley-peat of considerable depth and economic importance. Several of the small shallow lochs are surrounded with peaty deposits, and some of the peat bogs obviously occupy the sites of lochs which have been silted up. Some of the bogs are of great depth; the peat in the Moss of Skaill, S. of Stany Knowe, is said to be 30 ft. thick. Considerably the largest and most important bog is the Loan, less than a mile N.W. of Stromness, which is over a mile long from N. to S., and still contains a great deal of peat, although it has provided a considerable part of the fuel required by the town for 200 years. The deposit must originally have been very thick here.

There are small areas of blown sand and dunes at three places on the coast: at the Noust, just E. of the ruins of Breckness House; at Warebeth, a mile W. of Stromness; and on the S.E. side of the Bay of Sandside in Greamsay. The sand is a coarse shell-sand consisting of comminuted shells mixed with a small portion of flagstone debris. It is seldom more than 10 or 12 ft. thick. The largest area is that at Warebeth, which extends about a ¼ mile along the coast and nearly 400 yards inland. At Warebeth and Breckness much of the sand is cemented into a soft brown recent calcareous sandstone, often full of *Patella*.

The coast and foreshore usually consist of bare flagstones (with much seaweed between tide marks), but in the bays and geos there often lie considerable banks of coarse shingle or storm-beaches of more or less rounded slabs and pebbles of flagstone. On the W. coast the waves rise to an extraordinary height during storms, and at several places on the brow of the cliff where it is over a hundred feet high large slabs of flagstone have been shifted from their beds and tossed about in wild confusion for 20 or 30 yards back from the edge! The spray is carried far inland and

[1] *cf.* Flett (1920).

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the burns are so salt as to be undrinkable for nearly a quarter of a mile back from the cliff.

The famous Standing Stones of Stenness (the Circle of Stenness, the Circle of Brodgar, and a few isolated monoliths in the fields near), are on the eastern edge of the area, and are without exception slabs of the local flagstones, probably quarried near at hand. The largest slab stands over 16 ft. out of the ground, and must be nearly 20 ft. long over all.

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*Plate VI.*

Fig. 1. MARGINAL DEPOSITS OF THE GRANITE: The Conglomerate or Breccia of Granite fragments at the local base of the Middle O.R.S. South side of the Ness, Stromness. The section is about 10 feet high.

Fig. 2. View of the breccia of lava fragments in flagstone immediately above lava flow at Quoyelsh, Navershaw Bay.

*Plate VII.*

Fig. 1. TYPICAL GNEISS COUNTRY IN WESTERN LEWIS. Breasclete village.

Fig. 2. THE CARLOWAY OR DALEBEG GRANITE RIDGE (BEN GUIDAMOL), looking nearly N. from Creagan an Rathaid Mhoir, near milestone 9, across the valley of the Dalebeg Burn. The black line shows the approximate boundary of the granite. The road is mainly on scree. The quarries are near the far turn of the road.

*Plate VIII.*

Fig. 1. RED CONGLOMERATE. Near view of section on the shore near Vatisker Point. Height of bank on the right, about 10 ft.

Fig. 2. NEAR VIEW OF A VERTICAL TERTIARY DYKE of dark grey basalt in red conglomerate. This dyke is on the south coast of Vatisker Point, south of Coll village, and just east of the north end of Coll Sands. It is 20 ft. wide and the second largest in the district. The chilled margins are conspicuous.

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# PROCEEDINGS OF THE GEOLOGICAL SOCIETY OF GLASGOW. SESSIONS 1926-1927.

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SOCIETY'S ROOMS, 207 BATH STREET, GLASGOW, 11TH MARCH, 1926.

Sixth meeting of the sixty-eighth session, Mr. J. G. ROBERTS, Vice-President, in the chair.

Mr. H. H. Roderick exhibited a piece of sandstone with amphibian footprints. The specimen came from the Carboniferous of the Armadale district.

Dr. G. W. Tyrrell delivered Part 3 of his Presidential Address—"Igneous Action and Earth Movement in Scotland: The Kainozoic." (See *Geol. Mag.*, vol. lxiii, June 1926, pp. 285-286).

J. G. ROBERTS.

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SOCIETY'S ROOMS, 207 BATH STREET, GLASGOW, 8TH APRIL, 1926.

Seventh meeting of the sixty-eighth session, Mr. J. G. ROBERTS, Vice-President, in the chair.

Mr. R. B. Anderson read a note on "The Occurrence of a Deposit of Diatomite at Loch Osobhat, Lewis." (*See this volume*).

Dr. M. A. Peacock read a paper on "The Tectonics of the Faeroes." (*See this volume*).

A note on "The Reported Metamorphic Zone at Castlefern, near Moniaive, Southern Uplands," by Prof. J. W. Gregory, D.Sc., F.R.S., was communicated by the Secretary. (See vol. xvii, pt. 3, pp. 438-439).

G. W. TYRRELL.

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SOCIETY'S ROOMS, 207 BATH STREET, GLASGOW, 14TH OCTOBER, 1926.

First meeting of the sixty-ninth session, Dr. G. W. TYRRELL, President in the chair.

Mr. W. J. McCallien gave a preliminary account of the Post-Dalradian Geology of Kintyre. (*See this volume*).

Prof. Gregory congratulated Mr. McCallien on his paper, and asked if he had ever found in the Upper O.R.S. of this area anything like the structures described as fossils by Mr. John Smith in the Upper O.R.S. of Ayrshire. The Highland Boundary Fault ought to be regarded as of Middle O.R.S. age.

Mr. Richey suggested that the basal conglomerate might be the equivalent of the Downtonian conglomerate above the fish-bed in Lanarkshire.

Mr. Murray Macgregor asked if Mr. McCallien had done any detailed work on the Carboniferous sequence. Deep borings had been put down in the Machrihanish area, and evidence suggestive of the Millstone Grit lava-horizon of Ayrshire had been obtained.

Mr. Stark said that at Toward at Low Water the Lower O.R.S. is seen tilted at 60° as at Aberfoyle, and the Upper O.R. is actually in contact with the Lower and horizontal.

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The Chairman asked Mr. McCallien if the Lower O.R. has the same relation to the schists as the Upper. The Upper is normally undisturbed by Boundary Fault.

Mr. McCallien, in reply, said that so far he had not found time to make a systematic search for fossils in the O.R.S., and he had found no fish-bed near the base. He had not so far worked out the Carboniferous Limestone sequence, nor investigated the bore records referred to by Mr. Macgregor. He was aware that the Boundary Fault was of Middle O.R.S. age; what he objected to in the areas mentioned was the assertion that the junction of the Upper O.R. with the schists was a faulted one. In Kintyre the Lower O.R. lay in irregular hollows in the schists in exactly the same way as the Upper.

G. W. TYRRELL.

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SOCIETY'S ROOMS, 207 BATH STREET, GLASGOW, 11TH NOVEMBER, 1926.

Second meeting of the sixty-ninth session, the President, Dr. G. W. TYRRELL, in the chair.

The Chairman referred to the death, by drowning, of Mr. Leslie D. Currie, B.Sc., an Associate Member of the Society. Mr. Currie had only just joined the staff of the Burma Oil Co., as palaeontologist after a most successful career at the University of Glasgow, where he graduated in 1925. He was a member of the O.T.C. and a fine all round athlete. When he was appointed to the Burma Oil Co., he was holding a Carnegie Scholarship in the Geological Dept. of the University. His modest and winning personality had endeared him to his University colleagues and friends, and to his new colleagues in the Burma Oil Co. His untimely death at the age of 22 years is all the more regrettable as he was undoubtedly at the outset of a brilliant career in his chosen profession of oil geologist.

The President asked the meeting to instruct the secretary to send a message of sympathy to Mr. Currie's family.

Annual Business Meeting. Election of Office-bearers:—

President: Mr. Murray Macgregor, M.A., B.Sc.

The new President took the chair, and tributes were paid to the retiring President by the Chairman and the Rev. Dr. Ramsay Sibbald.

The other nominees for office were then elected:—

Vice-Presidents: Rev. Dr. S. J. Ramsay Sibbald; Mr. A. Stevens, M.A., B.Sc.

Members of Council: Mr. J. F. Scott, B.Sc.; Mr. Wm. Sinclair; Mr. W. Q. Kennedy, B.Sc.

Reports of Council, Finance, and Library were read by the Secretary, Treasurer and Librarian, and their adoption, moved by Mr. Steele, was carried.

Mr. J. F. Scott gave notice of a motion to be put to the next meeting of the Society, that a grant of £10 be made to the Library.

New Member: Miss Edith J. Wilson, M.A., proposed by Mr. J. L. Begg, seconded by Dr. J. Weir, was elected a member of the Society.

Prof. J. W. Gregory read a paper on "The Lochs of the Outer Hebrides." (*See this volume*).

The President in opening the discussion, said that Prof. Jehu and Mr. Craig had described the broken topography of the Outer Hebrides, which they attributed to the general foundering of the region, the indentations being the

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heads of the drowned valleys. They had also described 'goes', which in this region are often occupied by dykes.

Dr. G. W. Tyrrell said that he was pleased to learn that Prof. Gregory connected the E.-W. fractures (the oldest system) with the Alpine movements. The E.-W. and N.W.-S.E. fractures are frequently occupied by dykes; the E.-W. dykes are different in nature from the N.W.-S.E. and older, but probably not so old as we have been accustomed to regard them. Consideration of Scandinavian conditions suggests that they may belong to the early Kainozoic rather than to Hercynian times.

Mr. Stevens said the vertical clefts in the Caithness cliffs were probably the incipient stage in the formation of the 'goes,' which generally run at right angles to the local trend of the coast. The 'goes,' however, do not have at their mouths the characteristic threshold of fiords, and it is difficult to see why clefts in the O.R. cliffs of Caithness should have more significance than similar clefts elsewhere. The 'gutter' type of valley is probably just the result of a particular degree of drowning. What significance is to be attached to the local dominance of a particular direction, as in Moidart?

Prof. Gregory, in reply, said that he thought the direction of the quartz-dolerite dykes inconsistent with the general trend of the Hercynian lines. Prof. Jehu and Mr. Craig had found quartz-dolerite dykes in the Outer Hebrides with the same orientation as the Kainozoic dykes, and similar to them in degree of freshness. Local dominance of a particular direction is usually an adaptation to special local conditions, such as igneous intrusion. The further drowning of a fiord would give a fiard, not a gutter-valley; gutter-valleys are relics of the old drainage system, generally the consequent valleys.

M. MACGREGOR.

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SOCIETY'S ROOMS, 207 BATH STREET, GLASGOW, 9TH DECEMBER, 1926.

Third meeting of the sixty-ninth session, Mr. Murray Macgregor, President, in the chair. Apologies for absence were intimated from Prof. Gregory, Dr. Mackie, and Rev. Dr. Sibbald. Mr. J. F. Scott moved that a grant of £10 be made to the Library. This was agreed to. Prof. P. G. H. Boswell, University of Liverpool, read a paper on "Some Rare Detrital Minerals in British Sedimentary Rocks and their Significance." (*See this volume*).

The President and Dr. G. W. Tyrrell thanked Prof. Boswell for his paper and commented on the wide field of research which he had suggested to local workers. Dr. Tyrrell said that Dr. Mackie had recently found fluorspar in heavy residues from Arran granite, but the Survey chemist had been unable to find any trace of fluorine in the rock. Dr. Mackie had also obtained anatase from the quartz prophyry of the Corriegills shore and glaucophane in a schist from the St. Fillans district. Mr. Barrett had found minerals of the Arran granites in sand from the river bed in Glen Rosa, and amongst the light minerals, hyalite had been traced to its source in Judd's pitchstone dyke on Cir Mhor.

Mr. McLean asked if the colours seen on the screen were the actual body-colours of the minerals, or were they due to the staining of the mineral or the colouring of the slide?

Mr. Barrett said that he was interested in Prof. Boswell's information that andalusite was unlikely to travel far from its source. This would account

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for its scarcity in the alluvial sand of the Clyde. Dr. Mackie had found in an Aberdeenshire quartzite monazite which had been introduced during the intrusion of the local granite and not during sedimentation.

Prof. Boswell in reply, said that the tints shown on the screen represented by hand colouring, the body colour of the minerals. Where staining occurred in the mineral steps had to be taken to eliminate it. Prof. Boswell briefly indicated the techniques for the elimination of stains, the most efficacious being to boil in dilute HCl. with a fragment of tin. The body colour can be determined by grinding down—a process which he deplored. The occurrence of glaucophane in Scotland recorded by Dr. Mackie, although interesting, was not going to help in the interpretation of its occurrence in other British sediments, as the previous most northerly record was from N.W. Northamptonshire, whence it occurred in a stream right down to Brittany. He wished to utter a warning against pushing a good method too far—it was dangerous unless thorough, and deductions based on lateral correlation had to be made cautiously. The extraordinary complexity of variation in the sand dunes and shore sand around Scotland at the present day was greater than in any geological horizon. How was this to be explained? Conditions to-day were probably not very different from those prevailing during the deposition of some of the more recent deposits.

M. MACGREGOR.

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SOCIETY'S ROOMS, 207 BATH STREET, GLASGOW, 13TH JANUARY, 1927.

Fourth meeting of the sixty-ninth session, Mr. Murray Macgregor, President in the chair.

Dr. G. W. Tyrrell read two papers—(*a*) "Further Data regarding the Kainozoic Dykes of the Clyde Region," and (*b*) "Contribution to the Petrography of the Late-Palaeozoic Igneous Suite of the West of Scotland." (See *Geol. Mag.*, vol. lxiv, 1927, pp. 185-6).

Mr. J. E. Richey asked if the new S.S.E. direction of the Arran dyke-swarm was maintained into Ayrshire. Dr. Tyrrell replied in the affirmative.

The Rev. Dr. Ramsay Sibbald delivered a lecture on the Eastern Dolomites. With the aid of lantern slides Dr. Sibbald described the regions of the Dachstein and Schlern Dolomites, and demonstrated the distinctive topography of each. Dr. Sibbald thinks it is unnecessary to postulate extensive overthrusting in the interpretation of their mutual relationship in the field. The horizontal bedding of the Dachstein points to simple superposition on the Schlern. This interpretation, when considered along with the fact that Dachstein occurs as isolated caps on the tops of some of the Schlern mountains, and that these caps are remarkably uniform in altitude, points to a formerly continuous plateau of Dachstein, the erosive forces of the region being sufficiently potent, in Dr. Sibbald's opinion, to account for the enormous amount of denudation required to break up this plateau. Dr. Sibbald briefly discussed the theories advanced by V. Buch, Richthofen, and Mrs. Ogilvie Gordon to account for the origin of the Schlern Dolomite. The term 'dolomite' is generally inapplicable to the Dachstein formation.

M. MACGREGOR

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SOCIETY'S ROOMS, 207 BATH STREET, GLASGOW, 10TH FEBRUARY, 1927.

Fifth meeting of the sixty-ninth session, Mr. Murray Macgregor, the President, in the chair. The President announced that part 3, vol. xvii of the *Transactions* had been delivered by the printers.

Continuing the discussion of Dr. Tyrrell's papers from the previous meeting, Mr. J. E. Richey congratulated Dr. Tyrrell on the importance of his discovery of undersaturated lavas of Permian age in the Mauchline area.

Mr. J. F. Scott read a paper on the Geology and Physiography of Morvern. (*See this volume*).

The President congratulated Mr. Scott on his paper, and suggested that he should follow up this general account of the geology of Morvern with a detailed account of the different members of the succession and their relations to each other.

Prof. Gregory asked if Mr. Scott had observed any moraines, and if so, had he been able to determine their relations to the 100 ft. raised beach? Had he found any mollusca in the 100 ft. or 50 ft. beaches? He was pleased to learn that Mr. Scott had interpreted the depressions of the Sound of Mull and E. Loch Sunart as consequent valleys. It should be remembered that the old valleys of denudation are often modified by faults.

Mr. Richey asked if there was any relation between the two types of granite in the field. The cornstone at the base of the Trias occurred also in Ardnamurchan, and penetrated the underlying schists. The sandstone at the base of the Broadford Beds in Ardnamurchan he regarded as Trias, because of the absence of fossils. In Ardnamurchan the Pabba shales were unfossiliferous. Had Mr. Scott found any fossils in the Pabbas of Morvern?

Mr. Wilson asked if the metalliferous vein at Lurga cut the more recent rocks? Many boulders of Morvern granite had been found in Mull.

Mr. Simpson commented on the scenery produced by the different types of gneiss. The topography of the pelitic gneiss was more rugged than that of the semi-pelitic and psammitic.

Mr. Holmes said it was natural that the major drainage lines, especially the older consequent valleys, should be independent of the grain of the rocks, for not until the cycle of erosion has been in operation do such undersurface features as faults, and alternating hard and soft bands of rock affect the direction of flow of surface water.

Mr. Scott, in reply, said that there were no moraines in association with the 100 ft. raised beach, and he had found no shells in the 100 ft. and 50 ft. He had seen no junction between the red and grey granite; everywhere there was transition, and probably they consituted one intrusion. The fossils in the sandstone below the Broadford Beds are indeterminable casts. The Pabba shales are generally unfossiliferous. The intimate association of Triassic cornstone with the underlying gneiss occurs also in Morvern. Mr. Scott exhibited a specimen of the junction of the cornstone and gneiss, showing the penetration of the gneiss by the cornstone.

A. STEVENS.

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SOCIETY'S ROOMS, 207 BATH STREET, GLASGOW, 10TH MARCH, 1927.

Sixth meeting of the sixty-ninth session, Mr. A. Stevens, Vice-President, in the chair. Mr. H. H. Roderick, proposed by Dr. Weir and seconded by Mr. Duncanson, was elected a member of the Society.

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Mr. James Stark read a paper on "Buried Valleys in Clydesdale." (*See this volume*).

Prof. Gregory congratulated Mr. Stark on the confirmation of his early views on this subject, by the excavations for the new Power Station.

Mr. Geo. Ross said that he had visited the new shaft. There was a great thickness of fine-grained material which suggested a fluvio-glacial origin. Below the sand and gravel was boulder-clay with boulders fron the Douglas valley, Carboniferous rocks predominating. The upper fluvio-glacial material was derived from a wider area. Striae in the district indicates a general direction of ice-flow from the S.W. The succession of glacial deposits in the region showed (1) boulder-clay; (2) melt-stuff; (3) two terraces separated by coarse fluvio-glacial material.

Mr. E. B. Bailey delivered a lecture on "Domes in Scotland and S. Africa—Arran and Vredefort." With the aid of lantern slides Mr. Bailey illustrated such igneous structures as calderas, ring-dykes, cone-sheets and domes, and demonstrated the mechanism of their production. Mr. Bailey described examples of domes from Mull, Glencoe, Traprain Law, and Arran in Scotland, and from Vredefort in S. Africa. Mr. Bailey criticised the theory of centripetal pressure, advanced by Hall and Molengraaf to explain the Vredefort occurrence, and as an alternative suggested that the doming was due to the upward and centrifugal pressure of a granite younger than the one exposed which is older than the domed sediments.

Prof. Gregory said that the work of the Survey in Mull was an important contribution to our knowledge of the deep-seated volcanic proccesses. Cone-sheet fissuring was probably the cause of the circular distribution of some of the W. Coast fiords. The Vredefort granite was certainly older than the associated sediments. He congratulated Mr. Bailey on locating the fault on the N.E. side of the Arran granites; it was probably a continuation of the Loch Fyne fault. Mr. Bailey's explanation of the position of the Rhaetic beds in the central complex of Arran was preferable to the old view that they had fallen from above. The explanation of some of the structures dealt with confirmed Suess' view that many so-called intrusions were really due to the filling up of cavities.

Dr. Tyrrell said that he had found basalts on Ard Eheinn similar to the Kainozoic basalts of Mull, thus confirming the view that the first phase of igneous activity in Arran was the outpouring of basalt floods. The absence in the northern granites of Arran of the explosion debris which characterised the central complex suggested that the section of the northern granites was lower than that of the central complex. The fault on the N.E. suggested that the granite in doming had succeeded in fracturing the sediments. There were two granites in the N. and the mylonised edge associated with the younger indicated that it was responsible for the doming, and suggested an analogy with Vredefort. At Vredefort the younger granite was not so completely hidden as Mr. Bailey had implied. Small bosses and intrusions of alkali-granite and nepheline syenite were evidence of a later phase of activity than that represented by the old granite.

At this stage Mr. Bailey had to leave, and the meeting was concluded with a vote of thanks to the lecturer.

M. MACGREGOR

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# ABSTRACT

OF THE

# TREASURER'S ACCOUNTS.

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# ABSTRACT OF TREASURER'S ACCOUNTS FOR THE YEAR ENDING 30TH SEPTEMBER, 1926.

## CASH ACCOUNT.

### RECEIPTS.

| | | | |
|---|---|---|---|
| To Balance on hand 30th Sept., 1925:— | | | |
| Cash on Hand .. .. .. | 0 16 0 | | |
| Balance in Bank .. .. .. | £51 2 10 | | |
| | | £51 18 10 | |
| ,, Subscriptions:— | | | |
| Ordinary Members —79 at 15/- .. | £59 5 0 | | |
| Lady Members—7 at 10/- .. .. | 3 10 0 | | |
| Associate Members—10 at 2/6 .. | 1 5 0 | | |
| Life Members—1 at £5 5/- .. .. | 5 5 0 | | |
| Arrears—2 at 15/- .. .. | 1 10 0 | | |
| | | £70 15 0 | |
| ,, Interest on Investments .. | | | |
| £250 War Stock, 1929-47, (including Cowie Prize Fund).. .. .. | £12 10 0 | | |
| Funding Loan (James Neilson) .. | 4 4 0 | | |
| | | £16 14 0 | |
| ,, Library:— | | | |
| Sales of back numbers of Transactions Etc. .. .. .. .. | £16 17 0 | | |
| Sale of *Transactions* (1925) .. .. | 1 0 3 | | |
| Sale of *Transactions* (1926) .. .. | 0 10 6 | | |
| | | £18 7 9 | |
| | | £157 15 7 | |

### EXPENDITURE.

| | | | |
|---|---|---|---|
| By Library:— | | | |
| New book purchased.. .. .. | £0 9 3 | | |
| Geological Magazine .. .. .. | 1 10 0 | | |
| Outlays, postages etc. .. .. | 2 11 1½ | | |
| New books purchased (1926) .. | 2 10 1 | | |
| | | £7 0 5½ | |
| ,, Subscriptions:— | | | |
| Palaeontographical Society .. .. .. | | 1 1 0 | |
| Scottish Marine Biological Association .. .. | | 1 1 0 | |
| Natural History Society (use of Lantern) .. .. | | 1 1 0 | |
| ,, Cowie Prize Fund:— | | | |
| Glasgow Universtiy Interest to March, 1928 .. .. .. | £2 10 0 | | |
| Royal Technical College .. .. | £2 10 0 | | |
| | | £5 0 0 | |
| ,, Administration:— | | | |
| Rent, Lighting, Insurance and Attendance .. .. .. | 17 0 0 | | |
| Printing and Postage of billets .. | 14 17 1 | | |
| Honorary Secretaries', Treasurer's and Librarian's expenses .. .. | 2 12 8½ | | |
| | | £34 9 9½ | |
| ,, Cash on hand .. .. .. .. | £3 7 1 | | |
| Cash on Deposit Receipt .. .. | 70 0 0 | | |
| National Saving Certificates.. .. | 16 0 0 | | |
| On Current Account .. .. | 18 15 3 | | |
| | | £108 2 4 | |
| | | £157 15 7 | |

## LIFE SUBSCRIPTION ACCOUNT.

| | | | |
|---|---|---|---|
| Sept. 30, 1926.—To balance on hand .. .. .. | £250 15 0 | Sept. 30, 1925.—By balance on hand .. .. .. | £245 10 0 |
| | | ,, New Subscription .. .. .. | 5 5 0 |
| | £250 15 0 | | £250 15 0 |

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## COWIE PRIZE FUND.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Sept. 30, 1926.—To Glasgow University, one half of Interest to Martinmas, 1925 .. | £2 | 10 | 0 | Sept. 30, 1925.—By Balance on hand .. .. .. | 101 | 15 | 0 |
| ,, Royal Technical College, one half of interest to Martinmas, 1925 .. | 2 | 10 | 0 | ,, One year's interest .. .. .. | 5 | 0 | 0 |
| ,, Balance on hand .. .. .. | 101 | 15 | 0 | | | | |
| | £106 | 15 | 0 | | £106 | 15 | 0 |

## BALANCE SHEET.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| To Life Subscription Account .. .. .. .. | £250 | 15 | 0 | By Investments:— | | | | | |
| ,, Cowie Prize Fund .. .. .. .. .. | 101 | 15 | 0 | War Stock 1927-1949, including Cowie Prize Fund | | | | £250 | 0 0 |
| ,, Capital .. .. .. .. .. .. .. | 605 | 12 | 4 | ,, Funding Loan (James Neilson) .. .. .. | | | | 100 | 0 0 |
| | | | | ,, Property, Books .. .. .. | £440 | 0 | 0 | | |
| | | | | Furniture, bookcase and microscope | 60 | 0 | 0 | | |
| | | | | | | | | 500 | 0 0 |
| | | | | ,, Balance Cash on hand .. .. .. | £3 | 7 | 1 | | |
| | | | | Cash in Bank .. .. .. | 18 | 15 | 3 | | |
| | | | | ,, Deposit Receipt .. .. .. | 70 | 0 | 0 | | |
| | | | | War Savings Certificates .. .. | 16 | 0 | 0 | | |
| | | | | | | | | £108 | 2 4 |
| | £958 | 2 | 4 | | | | | £958 | 2 4 |

GLASGOW, *29th October*, 1926.—Examined, compared with relative Vouchers and Securities, and found correct, the Balance in Treasurer's hands being Three pounds, seven shillings and one penny sterling.

(Signed) ARCH. MACINTYRE, F.S.A.A., DUNCAN SMITH, F.F.S., } Auditors.

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# ABSTRACT OF TREASURER'S ACCOUNTS FOR THE YEAR ENDING 30TH SEPTEMBER, 1927.

## CASH ACCOUNT.

| 1927. RECEIPTS. | | | | | | EXPENDITURE. | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| To Balance on hand 30 Sept., 1926:— | | | | | | By Library:— | | | | | |
| Cash in hand .. .. .. | £3 | 7 | 1 | | | Geological Magazine .. .. .. | £1 | 10 | 0 | | |
| Deposit Receipt .. .. .. | 70 | 0 | 0 | | | New Books .. .. .. .. | 1 | 1 | 0 | | |
| Current Account .. .. .. | 18 | 15 | 3 | | | | | | | 2 | 11 | 0 |
| National Saving Certificates .. | 16 | 0 | 0 | | | ,, *Transactions* Vol. XVII Part 3 .. | £84 | 9 | 2 | | |
| | | | | £108 | 2 4 | Postages .. .. .. .. | 1 | 12 | 6 | | |
| ,, Subscriptions:— | | | | | | | £86 | 1 | 8 | | |
| Ordinary Members.—74 at 15/- .. | £55 | 10 | 0 | | | *less* Mitchell Library .. .. | 3 | 0 | 7 | | |
| Lady Members—6 at 10/- .. .. | 3 | 0 | 0 | | | | | | | 83 | 1 | 1 |
| Associate Members—7 at 2/6 .. | 0 | 17 | 6 | | | ,, Subscriptions:— | | | | | | |
| Arrears.—8 at 15/- .. .. | 6 | 0 | 0 | | | Palaeontographical Society .. .. .. .. | | | | 1 | 1 | 0 |
| Life Member.—One .. .. .. | 5 | 5 | 0 | | | Scottish Marine Biological Association .. .. | | | | 1 | 1 | 0 |
| | | | | £70 | 12 6 | Natural History Society (for use of lantern) .. | | | | 1 | 1 | 0 |
| ,, Interest on Invested Funds:— | | | | | | ,, Cowie Prize Fund:— | | | | | | |
| £250 War Stock, 1929-47 including Cowie Prize Fund .. .. | £12 | 10 | 0 | | | Glasgow University .. .. .. | £2 | 10 | 0 | | |
| Funding Loan (James Neilson) .. | 3 | 4 | 0 | | | Royal Technical College (interest to Mart., 1926) .. .. .. | 2 | 10 | 0 | | |
| | | | | 15 | 14 0 | | | | | 5 | 0 | 0 |
| ,, Legacies:— | | | | | | Administration:— | | | | | | |
| John Orr—Bequest .. .. .. | £49 | 5 | 2 | | | Rent, Lighting and Attendance .. | £16 | 15 | 0 | | | |
| Sir Michael Connel's Trustees—final instalment .. .. .. .. | 0 | 15 | 0 | | | Printing and postage of billets etc | 15 | 8 | 2 | | | |
| | | | | £50 | 0 2 | Hon. Secretaries and Treasurers expenses .. .. .. .. | £3 | 1 | 10 | | | |
| ,, Deposit Receipt—Interest .. .. .. .. | | | | £2 | 11 5 | | | | | 35 | 5 | 0 |
| ,, Sale of *Transactions* .. .. .. .. .. | | | | 0 | 7 6 | ,, Prof. P. G. H. Boswell's Expenses .. .. .. | | | | 3 | 15 | 0 |
| | | | | | | ,, National War Savings Certificate .. .. .. | | | | 65 | 12 | 0 |
| | | | | | | ,, Balances on hand:— | | | | | | |
| | | | | | | Balance in Bank .. .. | £34 | 17 | 7 | | | |
| | | | | | | Cash on hand .. .. .. .. | 14 | 3 | 3 | | | |
| | | | | | | | | | | 49 | 0 | 10 |
| | | | | £247 | 7 11 | | | | | £247 | 7 | 11 |

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## LIFE SUBSCRIPTION ACCOUNT.

| | | | | | |
|---|---|---|---|---|---|
| Sept. 30, 1927.—To Balance on hand .. .. | £256 | 0 | 0 | Sept. 30, 1926.—By Balance on hand .. .. .. | £250 | 15 | 0 |
| | | | | ,, New Subscription .. .. .. | 5 | 5 | 0 |
| | £256 | 0 | 0 | | £256 | 0 | 0 |

## COWIE PRIZE FUND.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Sept. 30, 1927.—To Glasgow University—one half interest to Mart., 1925 .. .. .. | 2 | 10 | 0 | Sept. 30, 1926.—To Balance on hand .. .. .. | £101 | 15 | 0 |
| To Royal Technical College—one half interest to Mart., 1925 .. .. | 2 | 10 | 0 | ,, One year's interest .. .. .. | 5 | 0 | 0 |
| To balance on hand .. .. .. | 101 | 15 | 0 | | | | |
| | £106 | 15 | 0 | | £106 | 15 | 0 |

## BALANCE SHEET.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| To *Life* Subscriptions Account .. .. .. .. | £256 | 0 | 0 | By Investments:— | | | |
| ,, Cowie Prize Fund .. .. .. .. .. | 101 | 15 | 0 | War Stock 1927-49 (including Cowie Prize Fund) | £250 | 0 | 0 |
| ,, Capital .. .. .. .. .. .. .. | 606 | 17 | 10 | Funding Loan (James Neilson) .. .. .. | 100 | 0 | 0 |
| | | | | War Savings Certificate .. .. .. | 65 | 12 | 0 |
| | | | | Property, Books .. .. .. £440 0 0 | | | |
| | | | | Furniture, Bookcase and Microscope 60 0 0 | | | |
| | | | | | £500 | 0 | 0 |
| | | | | ,, Balance, Cash on hand .. .. .. .. .. | £49 | 0 | 10 |
| | £964 | 12 | 10 | | £964 | 12 | 10 |

GLASGOW, *October* 26th, 1927.—Examined, compared with relative Vouchers and Securities and found correct, the balance in Treasurer's hands being Fourteen pounds, three shillings and three pence sterling.

(*Signed*) ARCH. MACINTYRE, F.S.A.A.
ALEXANDER MCLEAN. } Auditors.

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OF THE

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VOL. XVIII.—PART II.

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TRANSACTIONS

OF THE

GEOLOGICAL SOCIETY OF GLASGOW.

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# No. IX.—The North Ayrshire Sequence of Calciferous Sandstone Volcanic Rocks.

By J. E. Richey, M.C., B.A.

(With Appendix by A. G. MacGregor, M.C., B.Sc.)

(Read October 13th, 1927. Issued 1st September, 1928).

## I. Introduction.

The Area with which this communication is concerned includes a large part of the Clyde Volcanic Plateau south of the River Clyde (Fig. 27). It lies partly in North Ayrshire, but extends north and east into Renfrewshire and Lanarkshire. The original official survey was carried out chiefly by the late Professor James Geikie, and was completed in 1869. Practically no microscopic examination was made at that time, and the mapping of different types among the lavas was not attempted. During the recent revision by the Survey, petrography for field purposes has been chiefly under the supervision of Mr. E. B. Bailey. To him and also to Mr. A. G. MacGregor my acknowledgements for help received are especially due. I for my part have been concerned in the field chiefly with the easterly part of the Kilbirnie Hills, the Beith Hills and the uplands between Dunlop, Neilston and Eaglesham. A statement of the sequences met with in these districts, and their correlation with one another form the main subjects of this paper. Reference is also made to the work of other surveyors in adjacent districts. For permission to publish the results obtained, I am indebted to Sir John Flett, Director of the Geological Survey of Great Britain.

The base of the volcanic group is exposed for many miles along the west side of the Kilbirnie Hills, east of the Firth of Clyde, where it overlies Upper Old Red Sandstone. Further north-east, the Cementstone Group, the basal portion of the Carboniferous, intervenes at this position. Above the volcanic rocks there is a



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marked unconformity. The succeeding sediments that are known to overlap the volcanic series range from the upper third of the Oil-Shale Group[1] to the lower part of the Carboniferous Limestone.[2] The oil-shales are developed in the Strathaven district, 9 miles E.S.E. of Eaglesham, and there succeed the upper portion of the volcanic accumulations. They consequently set a higher limit to the age of the Calciferous Sandstone volcanic eruptions of the North Ayrshire region. These eruptions would appear to have occupied a relatively short period, extending from near the close of the Cementstone Group into the succeeding Oil-Shale Group.

The total thickness of the stratified volcanic rocks is estimated as at least 1000 feet west of Kilbirnie, and this amount is probably much exceeded further north and east. Southwards, towards Ardrossan, the volcanic series becomes greatly reduced, while eastwards of this place, in certain sections south-east of Galston, it is altogether absent.[3] The lavas were erupted from a number of volcanic vents, a conclusion already arrived at in other parts of the Clyde Plateau. They were for the most part poured out subaerially,[4] and at the close of the volcanic period must have formed extensive land.

Practically all the rock-types[5] found within the present area are known from other Calciferous Sandstone volcanic districts of Scotland. While local variations in the succession are everywhere encountered, two main stratigraphical groups can be recognised:—a Lower Group, characterized by macroporphyritic basalts mainly of Markle type, and an Upper Group in which olivine-rich microporphyritic basalts are the most widespread constituent. This Upper Group dies out south-westwards of Kilbirnie, but thickens out greatly towards the east by the addition of other types, which are chiefly of intermediate composition (trachytes, etc.).[6]

[1] Carruthers, R. G., *in* 'The Economic Geology of the Central Coalfield of Scotland, Area IX' (*Mem. Geol. Surv.*), 1921, p. 18.

[2] MacGregor, A. G., *in* 'Summary of Progress' for 1923 (*Mem. Geol. Surv.*) 1924, pp. 92-3.

[3] Richey, J. E., 'The Carboniferous Strata below the Top Hosie Limestone in North Ayrshire,' *Trans. Geol. Soc. Glasg.*, vol. xvii, pt. ii, 1925, pp. 205-6.

[4] *Ibid.*, pp. 206-7.

[5] For basalt types, see Appendix, p. 258.

[6] For petrographical descriptions of many occurrences in the Clyde Plateau, *see* G. W. Tyrrell, 'The Trachytic and Allied Rocks of the Clyde Carboniferous Lava-Plateaus,' *Proc. Roy. Soc Edin.*, vol. xxxvi, 1917, pp 288-299.

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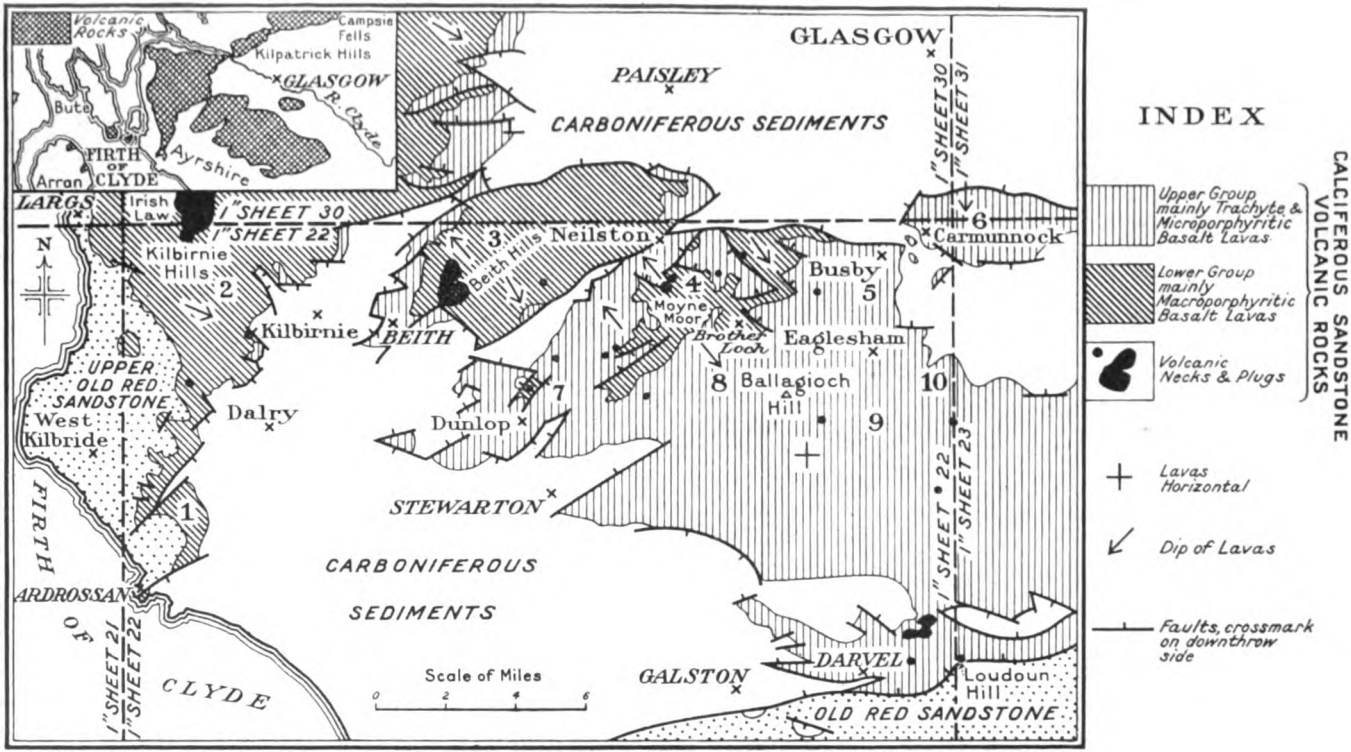


Fig. 27.—Map of Calciferous Sandstone Volcanic Rocks, North Ayrshire with parts of Renfrewshire and Lanarkshire.

Inset: Index-map of Clyde Plateau Lavas (Kintyre omitted). Note: Numbers 1—10 refer to localities given on Fig. 28. Sheet numbers refer to one-inch geological survey map of Scotland.

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The Upper Group is of especial interest since nowhere else in Scotland is an interbedded sequence of basaltic and trachytic lavas so well developed. It is necessary in the first place to state the evidence for the stratigraphical grouping outlined.

## II. Volcanic Succession.

The successions met with in various parts of the area are diagrammatically represented on Fig. 28. This figure is not intended to express an opinion as to the topography of the volcanic pile at any period in its formation. It cannot be known to what extent increase in height due to the volcanic accumulations may have been compensated by downward crustal movements. As an arbitrary datum-line, the junction of the two main stratigraphical groups has been drawn horizontal.

In the Kilbirnie Hills, mapped by Mr. G. V. Wilson and myself, the dip is uniformly towards the south-east. The Lower Group is persistent and is represented chiefly by Markle basalts, with occasional interbedded mugearites and olivine-poor microporphyritic basalts (Jedburgh type). The last-mentioned type is especially prevalent at the base (Fig. 28, 2). There are very few olivine-rich microporphyritic basalts, and only one recorded trachyte. The lavas of the Upper Group, with one exception, are olivine-rich microporphyritic basalts of Dalmeny type. These have been traced southwards from the Clyde near Erskine Ferry, in one-inch Sheet 30, by Mr. E. B. Bailey, and they disappear before reaching Kilbirnie. The small outcrop of the Upper Group shown on Figs. 27 and 28 south-west of Kilbirnie, consists of a local flow of rhyolite.

The Beith Hills structurally consist of a north-easterly extending anticline, the western half of which is well-exposed. The Upper and Lower Groups of the Kilbirnie Hills are recognised beyond any doubt, though in the Lower Group interbedded mugearites and Jedburgh basalts are almost everywhere absent. This Lower Group consists of the following portions (*see* Fig. 28, 3):—(*a*) a lower sequence of highly porphyritic Markle basalts; (*b*) an intercalated group of two thin flows of Dalmeny basalt, between which a lenticular, massive flow of Craiglockhart basalt is developed; (*c*) an upper sequence of Markle basalts, with a good proportion of Dunsapie basalts. The outcrop of the Upper Group fringing the Beith Hills is discontinuous owing to faulting, but its position

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above the Lower Group is established beyond question by field exposures north-east of Beith. It there consists solely of thin basalt flows of Dalmeny type, except for one interbedded macroporphyritic, though olivine-rich, basalt.

The uplands between Dunlop, Eaglesham and Darvel consist chiefly of the Upper Group, and outcrops of the Lower Group are only recognised in the north-west portion of the area. In this district the structure and succession may be best understood by approaching it from the Beith Hills by way of Neilston. South-west of the latter place, Dalmeny basalts are well developed, and are overlain to the west by Carboniferous sediments, as for example in a railway cutting near Pollick farm, between Neilston and Dunlop. These basalts therefore correspond to the Upper Group of the Beith Hills. Eastwards of their outcrop, and southwards of Neilston, they are underlain by a descending sequence of lavas, the lower portion of which consists of macroporphyritic basalts (Markle and some Dunsapie). These latter basalts are regarded as undoubtedly a portion of the Lower Group of the Beith Hills. They form the centre of an anticline around Moyne Moor. The lavas intervening between them and the overlying Dalmeny basalts include considerable thicknesses of Jedburgh basalt and porphyritic mugearite (Fig. 28, 4), which are not found in the Beith Hills. These intercalated lavas are most conveniently classed with the Upper Group. Mapping shows that they have a much more lenticular development than the overlying Dalmeny basalts.

South-east of the Moyne Moor Anticline to Ballagioch Hill, a complex sequence is met with, which consists mainly of trachytic lavas (rhyolites, trachytes and trachyandesites) with intercalated Jedburgh and Dalmeny basalts (Fig. 28, 8). Near Eaglesham, this assemblage includes thick beds of trachytic ash and agglomerate (Plate ix.), and is overlain by Carboniferous sediments (Enoch Burn). It therefore occupies the same position as the Upper Group of the Beith Hills, although it is much expanded, and Dalmeny basalts play a subordinate part in its constitution (Fig. 28, 9 and 10).

As the type section of the Upper Group in the Dunlop-Eaglesham area, I would select the belt of country stretching from Brother Loch south-east to Ballagioch Hill, a district mapped by Mr. G. A. Barnett, Mr. A. G. MacGregor and myself. The sequence is given on Fig. 28, 8, where it will be seen that two main trachytic

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positions are found, respectively below and above a series of microporphyritic basalts. The lower trachytic position can be traced over a considerable area east of the Moyne Moor Anticline. It is therefore a useful index-zone. Whether this extensive outcrop consists of one flow, or of a number of coalescent flows, is not known. While the horizon nowhere appears to be more than one flow thick, there is on the other hand a lateral variation in composition. The most usual type is trachyte, but locally trachyandesite and rhyolite (73.79 per cent. silica)[1] are met with. Southwards of Brother Loch, it forms the upper portion of a high scarp, while the lower ground to the west is occupied by the macroporphyritic basalts of the Lower Group. Immediately below its base, along the lower part of the scarp, a thin development of the porphyritic mugearites, already referred to from the Neilston district, and Jedburgh basalt, are met with. Elsewhere these lavas are usually absent, so that in such places the lower trachyte horizon directly overlies the macroporphyritic basalts.

Looking south-eastwards and in the direction of the dip from the ridge formed by the lower trachyte, a series of similarly disposed though less prominent scarps are seen to occupy lower ground for a distance of a mile. These are composed mainly of basalt lavas of Jedburgh type succeeded by others of Dalmeny type, and are finally surmounted by the massive trachyandesite of Bennan and Ballagioch Hills. Although direct contacts between lava-flows are rarely seen, there can be no doubt that the whole is an ascending series of lavas, and there is probably no faulting of importance. Further, the upper trachytic horizon for the most part differs in composition from the lower, for it is almost invariably a trachyandesite, containing about 58 per cent. silica.[2] While this upper horizon consists apparently of a single massive flow on Ballagioch and Bennan Hills, two or more successive flows can be recognised in certain other localities.

The basalts separating the two trachytic zones are not wholly microporphyritic. A flow of Dunsapie basalt is locally found immediately overlying the lower trachyte, while macroporphyritic basalt (Dunsapie or Markle type) occurs alongside the Bennan Burn a little below the trachyandesite of Bennan Hill. In this burn it overlies a bed of trachytic ash, which rests upon the

[1] Radley, E. G., *in* 'Summary of Progress' for 1923 (*Mem. Geol. Surv.*), 1924, p. 135.

[2] *Ibid.*

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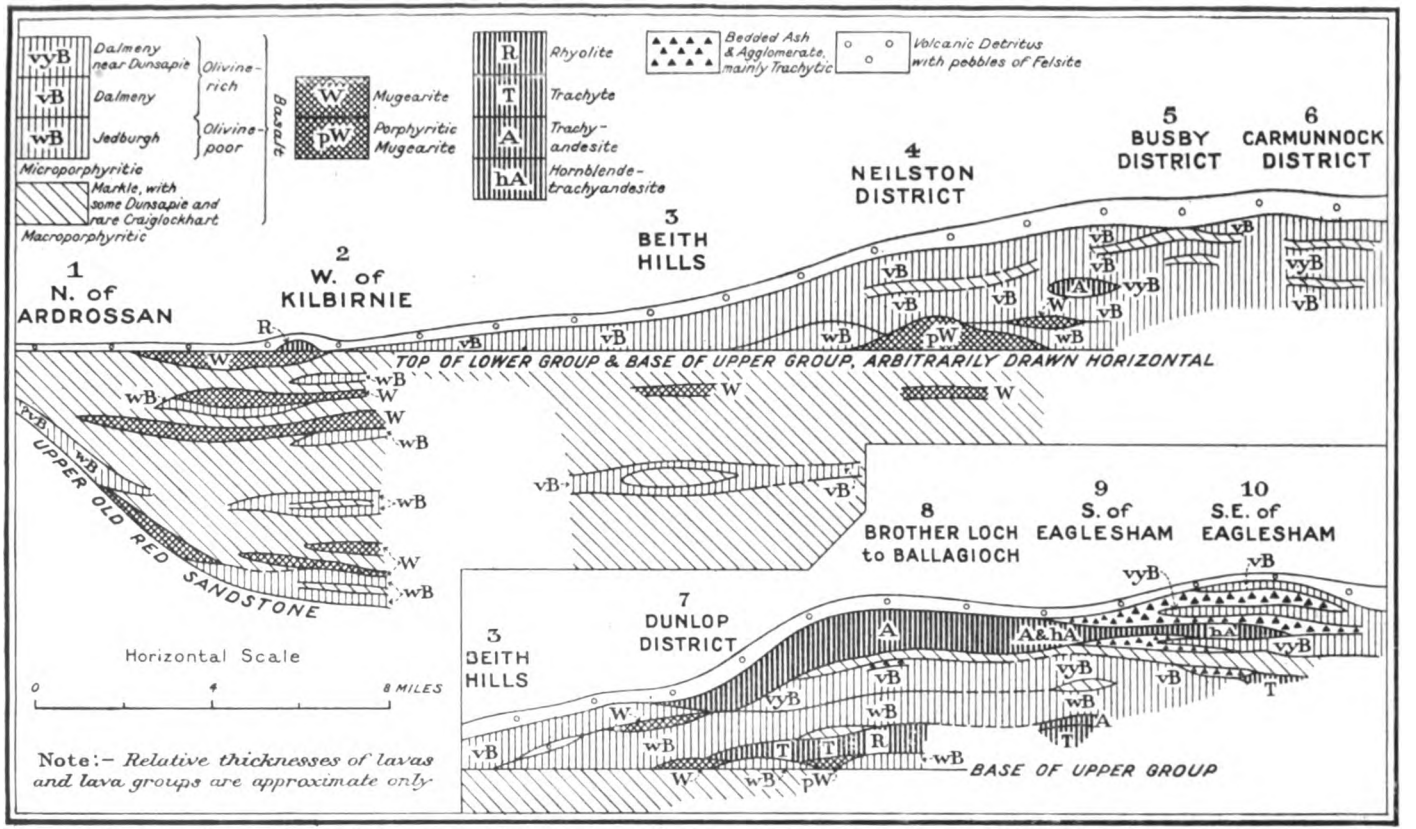


Fig 28.—Diagrams illustrating Local Variations within Calciferous Sandstone Volcanic Rocks, North Ayrshire with parts of Renfrewshire and Lanarkshire. For position of localities see map Fig. 27.

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top of an olivine-rich basalt with some felspar phenocrysts. The latter must in turn overlie typical Dalmeny basalt exposed downstream.

The uppermost portions of the trachytic lavas described above are seldom exposed, but probably little slag is developed, as in other trachytic areas.[1] They are, however, seen at the following localities (one-inch map, Sheet 22). The top of the lower trachyte is on view beneath a Dunsapie basalt just north of the outlet of White Loch, west of the Stewarton-Glasgow road. It is highly scoriaceous and without doubt that of a lava. A brecciated top is perhaps more usual, such as is exposed on the east side of Black Loch. In the case of the upper trachytic horizon, there is less direct evidence available. Trachytic breccias overlying more or less brecciated trachyte or trachyandesite are exposed in the Bennan Burn north-east of Bennan Hill, and are believed to represent the down-faulted top of the massive trachyandesite of Ballagioch. They are at any rate higher than this trachyandesite, for they give place down-stream to typical beds of volcanic detritus. There is additional evidence in the Eaglesham and Darvel districts, where recurrence of trachytic eruptions at various stages in the accumulation of the Upper Group is especially well demonstrated by interstratified trachytic ashes and agglomerates.

A remarkable feature is the localization of the trachytic rocks to a definite belt of country extending from between Dunlop and Neilston E.S.E. into one-inch Sheet 23. In illustration of this the two succession-diagrams of the Upper Group on Fig. 28 have been drawn. The sequence along the northern margin of the uplands, including localities 4, 5 and 6, consists chiefly of olivine-rich basalts with only a local development of trachyandesite. The sequence further south, for localities 7 to 10, includes the two main horizons of trachytic rocks just described, together with a thick development of trachytic ashes and agglomerates eastwards in the country between Eaglesham and Darvel. Again, still further south, the trachytic rocks are absent eastwards of Stewarton as far as the vicinity of Darvel, and the Upper Group consists of microporphyritic basalts only. The viscous character of trachytic lavas is well-known, and there is little doubt that their

[1] Daly, R. A., 'The Geology of Ascension Island,' *Proc. Amer. Acad. of Arts and Sciences*, vol. 60, no. 1, June, 1925, p. 75.

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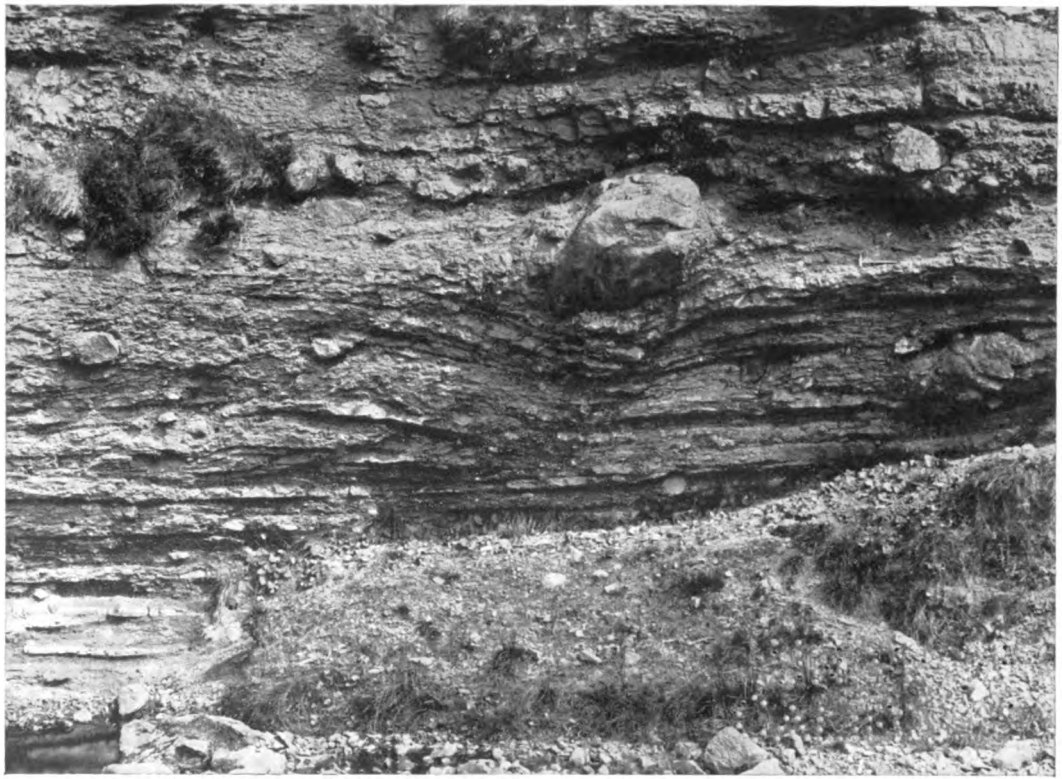

*W. Manson, Photo.*

TRACHYTIC AGGLOMERATE AND ASH AT CARROT, 2¼ MILES S. BY E. OF EAGLESHAM.

Note:—Local disturbance of bedding below one large 'bomb.'

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localized development in the present instance is governed by the distribution of the vents from which they originated. In agreement with this, we find a zone of trachytic vents extending from Irish Law E.S.E. to Loudoun Hill[1] (of the 21 vents shown on Fig. 27, 17 contain trachytic material). Of these, the large vents of Irish Law and the Beith Hills occur in districts where no corresponding bedded lavas or ashes are preserved.

The Irish Law vent is very complex, and Mr. G. V. Wilson has recorded basalt as well as trachyte within it.[2] He has also mapped felsite dykes and sills cutting the lavas and the Upper Old Red Sandstone of the Kilbirnie Hills to the south. It is probable that trachyte eruptions occurred here at the close of the volcanic period. At any rate, trachyte and felsite pebbles are abundant in conglomerates which, together with red mudstones, constitute a detrital group everywhere succeeding the lavas and ashes. The erosion responsible for the conglomerates extended down to Dalmeny basalts as is shown by the occurrence of pebbles of this type in the volcanic detritus at a point where these lavas are locally absent, viz., in the Millside Burn, a tributary of the Garnock Water, north of Kilbirnie. There is also little doubt that a large proportion of the reddish mudstone accompanying the volcanic conglomerates has resulted from the waste of basalt.[3]

## III. Comparison With Other Scottish Volcanic Areas.

The Carboniferous volcanic rocks of Scotland have been extensively studied in recent times by a number of workers. Both the varied petrology of the lavas and their succession have been the subjects of this research. While the succession shows in detail a recurrence of practically all the lava-types in no apparent order, the general sequence established in North Ayrshire seems to hold good elsewhere.

In Scotland generally, typical Markle basalt together with Jedburgh basalt and mugearite, constitutes a great part of the

[1] Richey, J. E., and A. G. MacGregor *in* 'Summary of Progress' for 1923 (*Mem. Geol. Surv.*), 1924, p. 89; *and* J. Phemister *in* 'Summary of Progress' for 1924 (*Mem. Geol. Surv.*), 1925, p. 105.

[2] Wilson, G. V., 'Preliminary Notes on Volcanic Necks in North-west Ayrshire,' *Trans. Geol. Soc. Glasg.*, vol. xvi, pt. i, 1916, Figs. 2 and 3, p. 89.

[3] Richey, J. E., *in* 'Summary of Progress' for 1919 (*Mem. Geol. Surv.*), 1920, p. 28.

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volcanic accumulations of Calciferous Sandstone age, and is succeeded in certain areas, in addition to North Ayrshire, by a trachytic and olivine-rich basalt phase. In East Lothian, Markle basalt is well-represented among the basic lavas that are overlain by the trachytes of the Garleton Hills,[1] while the latter are succeeded in time by olivine-rich basalts.[2] In the Firth of Clyde, Dr. W. R. Smellie has written concerning the lava sequence of South Bute that " in a broad and general way, the sequence is one beginning with intermediate lavas, mugearites, Markle and Jedburgh basalts, and passing into types on the one hand more basic, and on the other more acid."[3] Further south-west, in southern Kintyre, there is a considerable development of trachytic rocks associated with various types of basalt, including Markle basalt.[4] The volcanic suite rests unconformably upon Upper and Lower Old Red Sandstone and Highland Schists.[5] Possibly it may be comparable to the Upper Group of North Ayrshire, though this can be no more than surmised until Mr. McCallien's detailed examination of the sequence is concluded. In North Arran, a smaller development, consisting only of Dalmeny and Craiglockhart basalts,[6] is more readily comparable with the Upper Group, as developed in the Kilbirnie and Beith Hills.

In central Scotland, between North Ayrshire and East Lothian, the occurrence of late trachytic and felsitic eruptions is proved by necks piercing the suite of Markle and Jedburgh basalts and mugearites of the Campsie Fells.[7] This suite continues south-west into the Kilpatrick[8] and Kilbirnie Hills. Eastwards of the

[1] Hatch, F., ' The Lower Carboniferous Volcanic Rocks of East Lothian (Garlton Hills),' *Trans. Roy. Soc. Edin.*, vol. xxxvii, 1895, pp. 125-6.

[2] Barrow, G., and E. B. Bailey *in* ' The Geology of East Lothian ' (*Mem. Geol. Surv.*), 1910, chaps. 8 to 10, pp. 68 to 133.

[3] Smellie, W. R., ' The Igneous Rocks of Bute,' *Trans. Geol. Soc. Glasg.*, vol. xv, pt. iii, 1916, p. 344.

*See also* G. W. Tyrrell, ' The Igneous Geology of the Cumbrae Islands, Firth of Clyde, *Trans. Geol. Soc. Glasg.*, vol. xvi, pt. ii, 1917, pp. 246 and 272.

[4] McCallien, W. J., ' A Preliminary Account of the Post-Dalradian Geology of Kintyre,' *Trans. Geol. Soc. Glasg.*, vol. xviii, pt. i, 1927, pp. 70-71, 90-102 and 122-124.

[5] *Op. cit.*, Fig. 19, p. 63.

[6] Tyrrell, G. W., *in* ' The Geology of Arran ' (*Mem. Geol. Surv.*), 2nd edit., 1928, p. 57.

[7] Bailey, E. B., *in* ' The Geology of the Glasgow District ' (*Mem. Geol. Surv.*), 2nd edit., 1925, pp. 137-139, and pp. 147-148.

[8] Tyrrell, G. W., ' The Petrology of the Kilpatrick Hills,' *Trans. Geol. Soc. Glasg.*, vol. xiv, pt. iii, 1913, pp. 253-255.

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Campsies, olivine-rich microporphyritic basalts form a great assemblage of lavas at Bathgate[1] and also at Burntisland,[2] which extended in time from the upper Calciferous Sandstone throughout most of the Carboniferous Limestone period at Bathgate. Accompanying trachytic types are however unknown. This is also the case in recurring eruptions of olivine-rich microporphyritic basalt in Ayrshire during Millstone Grit times.

The above brief statement of the Scottish Carboniferous volcanic succession is to be taken as only applying " in a broad and general way." For Markle basalts are usually associated in any extensive accumulation with a small proportion of olivine-rich Craiglockhart basalt. Further, in East Lothian the earliest volcanic products seem to have been ashes of olivine-rich microporphyritic basalt, while at Arthur's Seat the lowest lavas are of Craiglockhart type.[3] It is, however, a notable fact that felspathic basalts were predominant in early stages of Scottish Carboniferous vulcanicity, while olivine-rich microporphyritic basalts became conspicuous at a later date, and were associated locally with trachytic rocks.

[1] Falconer, J. D., ' The Igneous Geology of the Bathgate and Linlithgow Hills,' *Trans. Roy. Soc. Edin.*, vol. xli, 1905, pp. 359-366.

[2] Allan, D. A., ' The Igneous Geology of the Burntisland District,' *Trans. Roy. Soc. Edin.*, vol. liii, pt. iii, 1924, pp. 479-484.

[3] Peach, B. N., *in* ' The Geology of the Neighbourhood of Edinburgh,' (*Mem. Geol. Surv.*), 1910, p. 59.

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## Appendix.

By A. G. MacGregor, M.C., B.Sc.

**Table showing Porphyritic Constituents of Carboniferous Basalts.**[1]

| Basalt-type. | Basic Plagioclase Felspar | | Augite. | | Olivine | | Constituent Phenocrysts. |
|---|---|---|---|---|---|---|---|
| | >2mm | <2mm | >2mm | <2mm | >2mm | <2mm | Dimensions of Phenocrysts |
| Markle | × | o | — | — | o | × | Macroporphyritic |
| Dunsapie | × | o | × | o | × | o | Olivine |
| Craiglockhart | — | — | × | o | × | o | Basalts |
| Jedburgh | — | × | — | — | — | o† | Microporphyritic |
| Dalmeny | — | o | — | o | — | × | Olivine |
| Hillhouse* | — | — | — | × or o | — | × | Basalts |

× = abundant; o = few (or absent).

† Microporphyritic olivine never absent, but less abundant than in Dalmeny type.

* Transition type between basalt and limburgite.

The ground-mass in all types consists of basic plagioclase felspar and augite, with iron-ore. In the Hillhouse type, the amount of felspar is much less than in the other types.

[1] For further details concerning the classification of the basalts, reference is directed to a forthcoming paper by Mr. A. G. MacGregor in the *Transactions*.

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# No. X.—A Further Contribution to the Petrography of the Late-Palæozoic Igneous Suite of the West of Scotland.

By G. W. Tyrrell, A.R.C.Sc., Ph.D., F.G.S., F.R.S.E. Lecturer in Geology, University of Glasgow.

(Read 13th January, 1927. Issued 1st September, 1928).

## Introduction.

It is intended in the present paper to give a more detailed description of the lavas and tuffs, and of the vent intrusions, of the Late-Palæozoic in Ayrshire, than was possible in an earlier publication (1912).[1] Field work and collecting has been carried on at intervals since 1909, but no attempt has been made at a complete survey, which is beyond the scope of a single individual, and is now, moreover, in the capable hands of the officers of the Geological Survey of Scotland (1922-26). Hence the notes as to field occurrences, geological features, etc. make no pretence to completeness. The petrography, however, has been done in more detail, and is based on the study of 215 thin sections in the collection of the Geological Department of Glasgow University, and of four new chemical analyses by Mr. W. H. Herdsman. These analyses have been made possible by the Carnegie Trustees for the Universities of Scotland, to whom grateful acknowledgement is due for their generosity in providing a grant.

To the late Sir A. Geikie belongs the credit for establishing the existence of this Late-Palæozoic volcanic field in the West of Scotland.[2] In his *Ancient Volcanoes of Great Britain*, he gave a very full description of the geology of the field,[3] and Dr. F. H. Hatch provided a brief note on the petrographical characters of the rocks.[4] In the same place Prof. W. W. Watts gave a short description of the contents of the vents, including the carbonated peridotite fragments of the Patna Hill vent, which were tentatively recognised as altered olivine nodules.[5] In his 1912 paper the

[1] Dates within brackets refer to the bibliography at the end of the paper.
[2] *Geol. Mag.*, 1866, p. 248.
[3] Vol. II, 1897, pp. 55-67.
[4] *Ibid.*, p. 57.
[5] *Ibid.*, p. 58.

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writer gave a short sketch of the petrography of the volcanic basin of Mauchline in central Ayrshire, and described some of the vent intrusions. In recent years the Geological Survey of Scotland has been engaged in revising the geology of the Ayrshire Coalfield, and in the course of the re-mapping many interesting new discoveries have been made with regard to the New Red Sandstone volcanic episode (*Summaries of Progress*, 1922-26, and Eyles, 1924), which will be referred to at the appropriate places in the text.

## Brief Sketch of the Geology of the Volcanic Field.

As this paper is mainly petrographical this section does not aim at being exhaustive. The volcanic field consists of two principal areas of lava flows, namely, Central Ayrshire, and Nithsdale, with numerous attendant volcanic necks and accompanying intrusions. The Nithsdale region is little known, and would make an attractive field of investigation. The best extant account is that by Sir A. Geikie.[1]

The lavas of Central Ayrshire occur in a ring-shaped outcrop about 9 miles in greatest width, and with a breadth of outcrop averaging about one mile. The towns of Mauchline and Tarbolton mark approximately the eastern and western edges respectively of the ring. The volcanic rocks form a saucer-shaped basin surrounding and underlying a more or less circular area of red sandstone with wind-rounded grains, which belongs to the lower part of the New Red Sandstone. They rest on the quite different red strata of the upper part of the Coal Measures, and their thickness has been estimated by Mr. D. Ferguson at 300 feet.[2]

The volcanic field consists of a number of thin, basic, lava flows (see Petrography, *postea*), with slaggy and scoriaceous upper surfaces, intercalated with tuff and red sandstone. The latter wraps round scoriaceous lumps and protuberances, and enters into the cracks and clefts of the lava flows. The sedimentary intercalations increase in number and thickness towards the top of the lava series until they merge into the overlying red sandstones, which continue to be more or less tuffaceous for some distance above the lavas. The best exposure of the transition is

[1] *Ancient Volcanoes of Great Britain*, vol. II, 1897, p. 60.

[2] Mr. A. G. MacGregor, of the Geological Survey of Scotland, informs me that over 500 feet of lava and tuff has been passed through in a boring at Tarbolton.

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to be seen in the gorge of the R. Ayr just above Ballochmyle Viaduct. Near Ochiltree an intercalation of sandstone occurs near the base of the series, and a thick bed of volcanic ash which underlies the sandstone, may represent the base of the volcanic series (1923, p. 82).

The lavas which immediately underlie the New Red Sandstone west of Loch Ryan, Wigtownshire, and at the head of the Sliddery Water in Arran, may possibly prove to belong to the same series. It is noteworthy that a considerable thickness of tuffaceous sandstone and volcanic breccia, containing numerous fragments of the typical red-speckled Permian basalts, occur towards the base of the New Red Sandstone series in Arran.[1]

The best sections in the Mauchline-Tarbolton lava basin are to be found in the gorge of the R. Ayr where, in its east to west course, it breaks through the low lava escarpment at Howford Bridge on the east, and above Stair on the west. The Lugar Water also provides a good section on the south-eastern side of the basin near Ochiltree, and the railway between Mauchline and Tarbolton occasionally gives a section in a cutting. Otherwise, apart from small quarries, exposures are rare and poor.

The vents from which these lavas have been emitted are rather widely scattered around the margin of the basin, especially on the northern side. Numerous vents also occur around the margin of the high Carboniferous plateau between Dalmellington and Patna, which may once have been covered by a sheet of lavas. Altogether, the vents assigned to this phase of igneous activity around the central Ayrshire and neighbouring areas, number about 60. They are all of the small "greenhill" type, characterised by bright green vegetation, and often sharply conical in form. They are generally filled with agglomerate composed partly of volcanic and partly of sedimentary material, which, like the lavas, is stained red or purple by ferriferous solutions. Very occasionally a plug of intrusive rock cuts across the fragmental infilling, as at Carskeoch and Carclout, near Patna (see p. 263). A thin skin of fresh lava is sometimes found adhering to the walls of these vents. The sieve-like perforation of the sedimentary rocks by these vents reminded Daly[2] of the Mid-Miocene vulcanicity of the Suabian Alb. He has also remarked their frequent association with sills,

[1] J. W. Gregory and G. W. Tyrrell, Excursion to Arran. *Proc. Geol. Assoc.*, XXXV, pt. 4, 1924, p. 414.

[2] Igneous Rocks and Their Origin, 1914, p. 298.

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and has adduced the Ayrshire and Fifeshire regions as examples of secondary vulcanism due to the opening of vents above hypabyssal intrusions.

The numerous and widespread olivine-dolerite, teschenite, crinanite, kylite, theralite, and other sills of Ayrshire and neighbouring counties, are believed to have been broadly contemporaneous with the vulcanicity of Central Ayrshire, and to represent its underground manifestations (Tyrrell, 1912, p. 129; 1923, p. 256). The teschenitic rocks cut strata up to the Coal Measures; the crinanite series, however, cut the New Red Sandstone lavas themselves (Howford Bridge, Mauchline). It is the purpose of this paper only to deal with those intrusions that are intimately associated with the vents, and these are described in more detail in the next section.

Monchiquitic types seem to be very closely connected with the vents, as at Patna, Carskeoch, Keirs Hill, and many other localities (Tyrrell, 1912, p. 127; Geological Survey, 1925, p. 95; 1926, p. 99). Bekinkinitic types (Carskeoch) and porphyritic essexite (Carclout) are equally closely associated with vents. The Geological Survey has recently stated that: "It is becoming probable that several of the New Red Sandstone necks pierce sills belonging to the teschenitic suite" (1926, p. 99). If this view proves well-founded, the date of the vulcanicity may be pushed well forward into the New Red Sandstone period, as the teschenitic series of the West of Scotland is definitely intrusive into strata high up in the Coal Measures.

## Description of some Vents and Associated Intrusions.

*Sorn Hill.* This vent forms an irregular protrusion on the north bank of the R. Ayr about one mile east of the village of Sorn. It consists of a pebbly agglomerate, with a good deal of finegrained matrix. Near the summit of the hill the vent material appears to be intruded by a small mass of basalt (see description, p. 271, and analysis, p. 273). The adjacent agglomerate is much indurated by this mass. New exposures made in 1912 during the laying-out of a golf course showed that the intrusive rock carried inclusions of sandstone, shale, and the agglomerate itself.

*Ashentree Glen.* This vent, which lies about 3 miles N.E. of Patna, is excellently exposed in a little gorge cut by a small burn. At its northern edge is red sandstone, against which, with an obscured contact, comes soft and decomposed agglomerate. The

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latter is reddish or purplish in colour, and contains numerous cobbles, but fewer boulders, in a matrix of lapilli of hazel-nut size. The boulders and pebbles consist of the usual red-speckled basaltic lavas, frequently very rotten and vesicular. Higher up the glen the agglomerate becomes sandy and finer in grain. Beds of stratified tuff appear, and even in the coarser agglomerate a rude bedded aspect becomes apparent. At the southern end of the gorge, and probably near the middle of the vent, is a small intrusion of dense, grey basalt (nepheline-basalt, see description p. 277, and analysis, p. 278), carrying greenish xenoliths of ultrabasic rocks. Its relation to the agglomerate is unfortunately not discoverable, but it appears to be of the nature of a plug.

*Patna Hill.* This vent, rising close to the village of Patna, is remarkable for the abundance of peridotite and monchiquite fragments it contains (1925, p. 95), a feature which it shares, however, with a number of vents in the same district (*infra*). The matrix of the agglomerate is made up of the usual hazel-nut size lapilli of basalt, with chips of shale, and lumps of sandstone, monchiquite, and peridotite. Numerous isolated crystals of biotite, and opaque white alkali-felspar (Eyles, 1924) occur, with hornblende and augite in smaller amount. These crystals have probably been separated from small fragments of a highly mafic rock consisting largely of hornblende and augite, and from others consisting of a highly micaceous lamprophyric type. Cobbles of carbonated peridotite are common, and cobbles and large boulders of baked quartzite, burnt black shale, and a black finegrained greywacke, have been obtained.

*Carskeoch Hill.* This vent is noteworthy for a remarkably variable intrusive complex, containing monchiquite, teschenite, bekinkinite, lugarite, camptonite, and crinanite, which appears to cut the agglomerate of a neck. The section (Fig. 29) shows the arrangement of the various types of rock. Carskeoch Hill is a narrow ridge elongated in an east to west direction. It lies one mile due south of Patna. The greater part of the hill consists of the various phases of a complex intrusion, the coarser parts of which form rocks of teschenitic, lugaritic, and bekinkinitic characters, the finer-grained parts rocks of monchiquitic character. There is also a relatively finegrained phase, rich in red hornblende and purple augite, which is termed camptonite. This complex intrudes sandstones and shales both of which are baked, the former into quartzite, the latter into a dense, black, flinty



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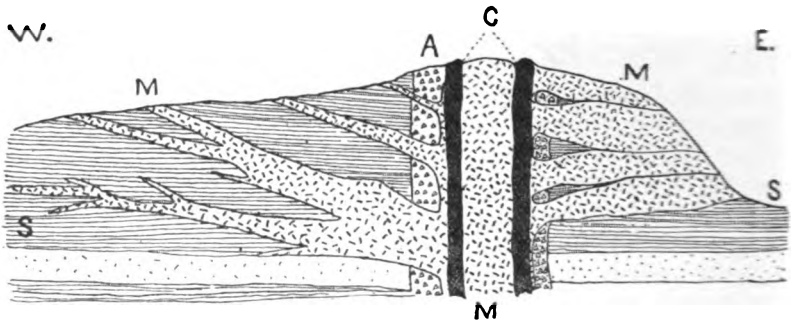
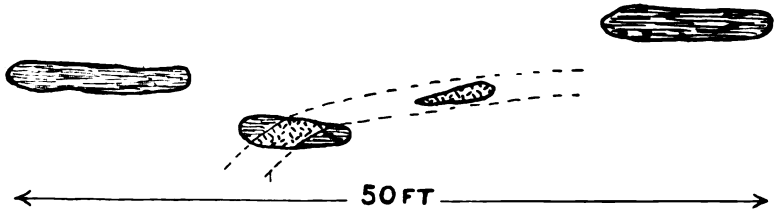
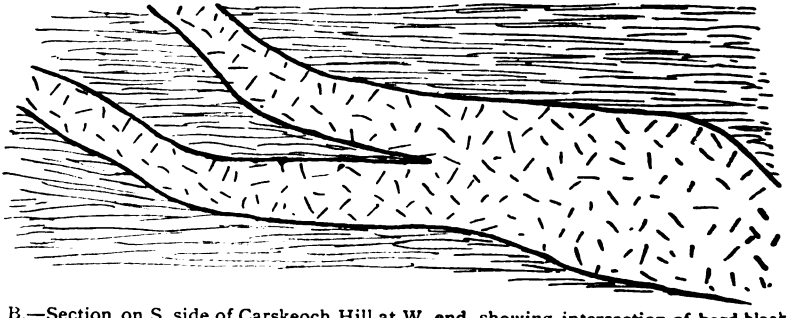



Fig. 29.—Section through Carskeoch Hill, Patna. Length of section ½ mile.
S.—Calciferous Sandstone sediments; A. Agglomerate:
M.—Monchiquite—teschenite—bekinkinite.
C.—Ring-dyke of crinanite.




A.—Plan of exposure on N. side of Carskeoch Hill near west end, showing vein of teschenite, etc., cutting flinty black shale.



B.—Section on S. side of Carskeoch Hill at W. end, showing intersection of hard black shale by monchiquite intrusion. Section about 6 ft. long.

Fig. 30.

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hornstone. The two sketches of exposure (Fig. 30) serve to illustrate some of the details of intrusion.

The intrusive complex also breaks through agglomerate of typical "Permian" composition, containing sporadic crystals of biotite and alkali-felspar. Agglomerate is exposed near the middle of the south side of the hill, and is cut in all directions by ramifying dykes and veins of monchiquite ranging up to one foot in thickness. There is another exposure near the eastern end of the hill on the south side, just east of a fence. Practically the whole of the eastern end of the hill consists of monchiquitic and teschenitic rocks, and it is here that the best spots are found for collecting extraordinarily large xenocrysts of hornblende and biotite.

A little east of the 845′ O.D. there is a rocky knoll consisting partly of a uniform, fresh, grey, olivine-dolerite with analcite, or crinanite ("essexite-dolerite of Carskeoch type," see Tyrrell, 1912, p. 120), of characters very different to those above-described. The exposure of this rock, which weathers into large cuboidal masses, appears as an almost complete ring surrounding decomposed bekinkinite and camptonite, into which it is probably intrusive although no decisive evidence of this relation could be obtained.

The history of the Carskeoch vent seems to be as follows: A volcanic vent broke through the Calciferous Sandstone Series here consisting of sandstone and shale. The funnel was filled with the usual detritus of basaltic lavas, sedimentary fragments, monchiquite blocks, and xenocrysts. At a later stage a teschenite—bekinkinite—monchiquite intrusion partially eviscerated the vent, and spread as ramifying sill-like masses into the adjacent sediments. Finally an intrusion of olivine-dolerite of crinanitic type came up along the walls of the plug, forming an annular intrusion somewhat resembling a ring dyke.[1]

*Carclout.* Carclout Hill is situated about 2½ miles W.S.W. of Patna. It is a vent filled with a fairly-hard, compact agglomerate, the fragments of which average walnut-size, but range up to the size of the fist, large boulders being very rare. Pebbles of the

[1] From a further and more complete survey of Carskeoch Hill and the surrounding country, Mr. A. G. Macgregor of the Geological Survey of Scotland, has come to a somewhat different explanation of the history of this vent. In particular he has shown that the monchiquite sills extend a long way beyond the confines of Carskeoch Hill into the adjacent rocks.

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red-speckled Permian lavas are abundant, and in places the rock is full of dark, lustrous, augite crystals. These crystals have undoubtedly been derived from the same magma as a small boss of porphyritic essexite which cuts the agglomerate. This mass is elongated in an east to west direction, and is not more than 50 yards long by 20 yards wide. It is seen in a small quarry that was opened to build a dyke, and in small scattered exposures to the west. The rock appears to be identical with the porphyritic essexites of Crawfordjohn and Lennoxtown.

*Keirs Hill.* Keirs Hill is situated about 2½ miles W.S.W. of the village of Waterside, and about 1½ miles S. of Carskeoch. At the northeastern end of this vent the exposures show a hard, blue, brecciated monchiquite containing numerous xenoliths of sandstone and shale, and xenocrysts of pyroxene, amphibole, biotite, and alkali-felspar. Occasionally these crystals are aggregated so as to form a porphyritic monchiquite like that of Carskeoch. There are also infrequent pebbles of ultrabasic rocks, and what appear to be olivine nodules. Some true agglomerate, which weathers with a very slaggy surface, is also seen. It contains some very large boulders of quartzite, sandstone, and shale.

## Petrography.

The rocks to be described may be classified as follows:—

A. Lavas, and lavaform masses and fragments in the vents.

1. Olivine-basalt, *cf.* Dalmeny type, but with a little analcite, etc. in the groundmass. In this group some rocks show a variation in the ultrabasic direction, producing basalts very rich in augite and olivine, especially the former. These types are comparable with the ankaramite of Lacroix[1].
2. Analcite-basanite. By an increase in the amount of mafic minerals and analcite, etc., with a correlative diminution in the amount of felspar, the above olivine-basalts pass into types which may be termed analcite-basanite, by analogy with the corresponding nepheline- and leucite-bearing rocks, in which felspar still remains an essential constituent. In this group also there is a variation towards an ultrabasic modification, leading to olivine-basalts of Hillhouse type.

[1] *Comptes Rendus*, Paris, tom. 163, 1916, p. 182.

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3. Analcite-basalt (or monchiquite lava), nepheline-basalt, and limburgite. Ultrabasic types with a minimal amount of felspar, or felspar absent. Nepheline, of course, is the predominating felsic constituent in the nepheline-basalts, analcite in the analcite-basalts, whilst glass takes the place of either or both these constituents in the limburgites.

B. Bekinkinite, teschenite, camptonite, monchiquite, crinanite, and essexite. Intrusive rocks of the Carskeoch, Carclout, and Keirs Hill vents.

C. The agglomerates and tuffs, with their contained fragments other than basaltic lavas.

The olivine- and augite-nodules, and peridotite xenoliths, which occur included within the lavas or lavaform masses of the vents, will be described in the appropriate places under the heading A. The ultrabasic igneous rocks and other materials which occur as fragments in the vents will be described under C.

A. The lavas, and lavaform masses and fragments in the vents.

*Macroscopic Characters.*

Excluding a few rare felspathic types the lavas and lavaform rocks are of singularly uniform characters as regards their macroscopic appearance. They are all compact and aphanitic, the colour ranging from dark red to purplish, rarely grey or black. A very characteristic aspect is imparted by the universal red speckling due to the replacement of numerous microporphyritic olivine crystals by red iron ore. A red stain of diffused haematitic material frequently gives the rocks an appearance of decomposition which is belied by the general freshness apparent in thin section. The pyroxenes and felspars are usually quite fresh, but the analcite is frequently, and the olivine nearly always, decomposed. The general red staining and the pseudomorphous replacement of olivine by haematite, are no doubt due to the downward percolation of waters charged with ferriferous materials from the overlying red sandstones. Large phenocrysts are rare. Olivine is the most abundant phenocrystic mineral; augite is occasionally seen; but felspar practically never. The rocks are often highly amygdaloidal. The steam cavities are usually of irregular shapes, but sometimes spherical, and contain calcite or a soft, waxy, "green earth."

*Microscopic Characters.*

The microscopic characters of the constituent minerals of these rocks are remarkably uniform throughout the whole series, and in

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order to avoid undue repetition in the ensuing petrographical descriptions, a general account of the minerals is given in this place.

*Olivine* occurs abundantly as small microphenocrysts only distinguishable from the elements of the groundmass by their slightly greater size. Only rarely do they attain phenocrystic dimensions. The crystals are generally quite idiomorphic, giving the usual regularly hexagonal outlines, and varying in size from 1/5th to 2 mm. The olivine appears to have been very susceptible to alteration, as it is nearly always pseudomorphed by haematite or serpentine, or both. A common appearance is for the interior of a crystal to be occupied by serpentine, while red iron ores form broad irregular bands along the margins and cracks. Frequently, however, haematite replaces the whole crystal. The serpentine is of various colours, green predominating; but it may be deep red, laminated, and highly pleochroic (iddingsite ?); in other sections it may be orange, pale yellow, or colourless.

*Augite* occurs both in the groundmass and as phenocrysts. Its colour varies from pale purple to colourless, but in the phenocrysts the purplish tint tends to deepen around the margins of the crystals, and the interiors may take on a faint tinge of brownish green. The mineral is only feebly pleochroic. In the groundmass the grains are usually rather shapeless, and often of a comparatively deep colour. The phenocrysts, on the other hand, are well-shaped, and occasionally show a twin-lamellation parallel to (100), confined to the central parts of the crystals. The extinction angle ranges up to 45°.

The phenocrystic augite frequently occurs as large, polysomatic masses of mutually-interfering crystals. It encloses olivine and iron ore, and is thus of later consolidation than these minerals. When thus protected from the iron-bearing solutions, which seem to have had no effect on the augite, the olivine is usually quite fresh or only slightly altered.

*Felspar* in the basic lavas is a plagioclase the extinction-angle of which does not vary much on either side of 30°. It is therefore an acid labradorite of the composition $Ab_1An_1$. Occasionally the extinction-angle corresponds to a composition $Ab_2An_3$. The crystals are usually quite idiomorphic, and form lath-shaped sections; but some broad, untwinned, zonary plates of late consolidation occur, and enclose earlier augite crystals along their

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margins. The twin-lamellae of the labradorite are frequently very thin and wire-like, and wedge out before traversing the whole length of the crystal.

*Analcite* may occur as a more or less pervading base filling up angular interstices between the other minerals, or it may appear in little, isolated, rounded areas up to 1 mm. in diameter, which may represent vesicles filled with residual liquid. Occasionally the analcite becomes relatively abundant, and the mineral may then occupy large, irregular areas comparatively free from enclosed felspars and pyroxenes. It is rarely quite fresh, and is mostly altered with the production of a brown dust; it may occasionally be found quite pellucid and fresh. In an extreme phase of alteration it is replaced by calcite, radial zeolites, or an indeterminate, colourless or pale green, vermicular, minutely-spherulitic, or cryptocrystalline substance. The mineral is generally free from microlites of any kind except apatite needles, but it may envelop detached or projecting crystals of felspar or augite. On the margin of a section, cubic cleavage lines can sometimes be detected in the analcite areas.

*Iron Ores* are not abundant apart from the haematite pseudomorphs after olivine. Magnetite occurs as minute idiomorphic crystals in the groundmass, but never in any considerable quantity. In the coarser rocks, however, small, ragged, skeletal masses occur in some abundance, and are probably to be referred to ilmenite.

*Nepheline* occurs in some of the more basic lavas as small crystals in the interstices between the other minerals. It is allotriomorphic to felspar, but idiomorphic to analcite. Slightly turbid and streaky, straight-sided, crystals with poor terminations, are usual. They give straight extinction parallel with the straight sides and the direction of the streakiness, and have a negative optical sign. Nepheline may also form small plates poikilitically enclosing the other constituents of the rock.

*Glass*, which occurs chiefly in the limburgites, is usually tinted brown, frequently of a very dark shade, and is often crowded with hair-like crystallites, or arborescent growths of iron oxide. It is always quite isotropic, and occurs only in the angular interspaces between adjacent crystals, which never show signs of corrosion and replacement, as they frequently do near analcite. It cannot often be confused with analcite, but in some cases, owing to alteration or minuteness of section, the distinctive

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criteria fail, and the nature of the isotropic base must be left in doubt.

The *textures* of these lavas are uniformly intergranular and microporphyritic, that is, they possess microphenocrysts of olivine, augite, and felspar, especially the first-named mineral, in some abundance, enveloped in a groundmass consisting of lathy felspars, granular augite and iron ores, in which the augite granules are packed away between the elongated felspars. Occasionally the felspars are arranged with a marked flow structure. The great majority of the rocks are holocrystalline; analcite or a greenish cryptocrystalline substance often fills the small interspaces; only rarely is there any glassy matter present. A slight variation arises occasionally from coarser grain size, when a doleritic type is produced by the appearance of comparatively large aggregates of augite granules between the felspar laths. Hardly ever is there any approach to an ophitic texture.

1. *Olivine-basalt, cf. Dalmeny type.*

Rocks of this character comprise the majority of the lavas of the Mauchline basin, and of the lavaform blocks and pebbles in the vents. The commonest variety is one that compares well with the Dalmeny basalts of the Lower Carboniferous in the Midland Valley of Scotland, with the exception that it always appears to contain a little residual analcite. In thin section these rocks show abundant microporphyritic olivine, pseudomorphed by haematite and serpentine, embedded in a groundmass made up of purplish granular augite, lathy plagioclase ($Ab_1An_1$), and sparse iron ores, the first-named usually predominating. Close search will almost invariably reveal a little analcite filling interspaces between the other minerals.

Lavas of this character occur W. of Howford Bridge; in the quarries on Mauchline Hill; at Broomhouse Braes on the Lugar Water near Ochiltree; in the Trabboch Burn near Stair; in the old quarries of the Alton Burn, Tarbolton; and at Barnweill Hill. They occur also as pebbles or boulders in the agglomerate of the following vents: Littlehill; Boghall Smithy near Galston; Castlehill, near Kilwinning; Shewalton Mill, Dundonald; Treesbank, Riccarton; Greenhill, E. of Stannery Knowe, Rankinston; Spy Knowe, Waterside; Kirklafinn, 1 mile S.S.W. of Patna; Carclout, Patna; Polnessan Burn, 1 mile N.E. of Patna; Dunston Hill, 2 miles N.E. of Patna; Ashentree Glen, 3 miles N.E. of Patna; and High Knockshinnoch, 3 miles N.N.E. of Patna.

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Another quite common variety of these lavas is one in which the microporphyritic olivine is supplemented by augite and very occasionally by felspar. These rocks may thus be regarded as microporphyritic analogues of the Craiglockhart and Dunsapie basalts of the Lower Carboniferous in the Midland Valley of Scotland, although the abundance of microporphyritic olivine justifies their retention in the Dalmeny basalt group as defined above. The augite often occurs in large or small polysomatic aggregates, producing what may be regarded as augite nodules, or cognate xenoliths of pyroxenitic composition. Analcite is frequently more abundant in this type than in the above-described Dalmeny basalts; and the rocks are often transitional to the analcite-basanites described in the next section. A tendency to considerable predominance of the mafic minerals over the felspars is another feature of this group, which it also shares with the analcite-basanites.

The analysed rock (Table I, 1), which forms a small intrusive mass within the vent of Sorn Hill near Catrine (p. 262), is a typical example of this group. In thin section it consists of a plexus of broad plagioclase laths with good lamellar twinning ($Ab_2An_3$), and shapeless grains of deeply-coloured purplish augite, with rather abundant, small, ragged, skeletal crystals of iron ore which is probably titaniferous. Analcite occupies large polygonal cavities usually bounded by felspar laths. It is occasionally fresh and clear, but most often it is altered wth the production of a greyish dust. In this condition it is still isotropic; but in a more extreme phase of alteration it is replaced by calcite and "green earth." It contains detached granules of augite, always of a deep purple colour; and envelops projecting felspars which appear to have suffered some corrosion. Phenocrystic olivine is represented by abundant small pseudomorphs in a pleochroic red serpentine. Augite also occurs porphyritically in abundant, large, polysomatic aggregates. The phenocrystic augite is of a much paler tint than that of the groundmass, and the purple coloration is often confined to a thin marginal zone, the interiors of the crystals being pale brown. The lamellar twin striation parallel to (100) is prominent. A little felspar and iron ore take part in the polysomatic aggregates.

A peculiar aggregate, about 1.5 mm. in diameter, consisting of minute, closely-packed granules of augite, occurs in one part of the slide. A few grains of iron ore, and a few felspar laths, are

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also enclosed. Around the margin of the patch is a broad zone of much larger augite granules. The aggregate much resembles the patches produced by the assimilation of foreign siliceous matter in a dolerite or basalt.

There are a few plates of zonary untwinned felspar of late generation, enclosing augite and magnetite around their margins, Occasionally the labradorite laths pass into a clear, untwinned, and unzoned felspar at their margins, and this exterior zone may extend into, and fill up, an adjacent interspace. This mineral is probably orthoclase, and contains the potash disclosed by the analysis. Some interstices are filled with a base consisting of plagioclase, augite, and iron ores, of much finer grain than the rest of the rock. Apatite crystals are abundant, especially in the interstitial material.

Lavas more or less similar to the above are found in the R. Ayr both east and west of Howford Bridge; and in the Dippol Burn N. of Ochiltree. As constituents of the vent-agglomerates they occur at Bruntwood Farm, Galston; Treesbank, Riccarton; Little Sorn Burn, Mauchline; Gibston Braes, Lugar Water; but they are especially abundant in the agglomerate of the Carclout vent, W. of Patna. Here the lava fragments carry numerous augite nodules, and the felspars exhibit well-marked flow textures.

It has been mentioned above that the lavas of this group exhibit a tendency for the mafic constituents to preponderate over the felsic. In extreme cases this tendency produces rocks of ultra-basic composition, extremely rich in augite and olivine. Types such as this are comparable with the *ankaramite* of Lacroix (see p. 266). Two good examples are lavas from an old quarry at the top of the hill ½-mile N. of Auchinweet, Mauchline; and from an old quarry at the Wallace Monument, Barnweill, near Tarbolton.

The *chemical composition* of members of the above-described group of rocks which contain microphenocrysts both of olivine and augite, is illustrated by the analysis of the Sorn Hill intrusion (Table I, 1), wherein its general resemblance to an analysis of a Dunsapie basalt from the Kilpatrick Hills, and to the analcite-basanite of Stair, is exhibited. On account of the haematisation of the olivine, and the pervading stain of red iron oxide, the relations of ferric and ferrous iron oxides in this rock are the reverse of what is usual in basalts of this type, as can be seen if it is compared in this respect with the fresh rock from Stair (Table I,

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2). Along with low silica there is present high lime and alkalies, which, in the calculation of the norm (Table III, 1), leads to a relatively large amount of basic plagioclase ($Ab_2An_3$), and to the presence of 5.4 per cent. of normative nepheline. This mineral, of course, appears modally as analcite. The relative poverty in olivine disclosed in the norm is due to the transformation of a considerable amount of FeO, which otherwise would have gone to olivine, to $Fe_2O_3$, thus augmenting the amount of iron ores in the rock at the expense of olivine. No doubt some magnesia has also been lost in this reaction.

If we regard the norm of this rock as representing quite closely its modal composition, as it certainly does so far as the ratio of felsic to mafic constituents goes, then its *felsicity* is 57.5, *i.e.* the felsic constituents make up 57.5 per cent. of the rock. Its *colour ratio* (Shand[1]) will be 42.5.

TABLE I.

| | 1 | A | 2 | B | C |
|---|---|---|---|---|---|
| $SiO_2$ .. .. .. | 43.40 | 45.10 | 44.20 | 46.28 | 43.94 |
| $Al_2O_3$ .. .. | 16.44 | 15.04 | 15.04 | 14.18 | 15.44 |
| $Fe_2O_3$ .. .. | 8.25 | 8.85 | 1.56 | 3.79 | 3.90 |
| FeO .. .. .. | 3.49 | 4.62 | 9.52 | 7.34 | 8.25 |
| MgO .. .. .. | 6.15 | 6.68 | 10.26 | 10.82 | 9.64 |
| CaO .. .. .. | 11.70 | 8.71 | 10.13 | 9.88 | 10.56 |
| $Na_2O$ .. .. | 3.10 | 3.78 | 3.46 | 2.58 | 2.81 |
| $K_2O$ .. .. .. | 1.75 | 1.04 | 1.15 | 1.01 | 1.34 |
| $H_2O+$ .. .. | 1.88 | 1.76 | 1.85 | 1.66 | 2.33 |
| $H_2O-$ .. .. | .30 | 1.31 | .20 | .31 | .19 |
| $TiO_2$ .. .. .. | 2.00 | 2.66 | 1.95 | 2.06 | 2.03 |
| $P_2O_5$ .. .. .. | .32 | .56 | .32 | .44 | – |
| MnO .. .. .. | .09 | .45 | .14 | .09 | tr. |
| $CO_2$ .. .. .. | 1.10 | nil | tr. | nil | – |
| S .. .. .. | nil | – | nil | nil | – |
| (Ni, Co)O .. .. | nil | – | nil | .05 | – |
| (Ba, Sr)O .. .. | – | .04 | – | nil | – |
| F, Cl .. .. .. | – | – | – | nil | – |
| | 99.97 | 100.60 | 99.78 | 100.49 | 100.43 |

[1] S. J. Shand, *Eruptive Rocks*, 1927, p. 131. Shand's colour ratio is the percentage of heavy (or dark) minerals. I prefer to state the percentage of light, felsic (or salic) minerals, because, when the ratio of light to heavy minerals is computed from the norm, as it must be in many cases, any alter-

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1. Olivine-basalt, with some analcite in groundmass (*cf.* coarse Dalmeny type[1]), approaching analcite-basanite. Intrusion in agglomerate, Sorn Hill, Ayrshire. Anal. W. H. Herdsman.

A. Olivine-basalt, Dunsapie type, Duncomb Hill, Kilpatrick Hills, Dumbartonshire. Anal. A. Scott. Quoted from G. W. Tyrrell, The Petrology of the Kilpatrick Hills. *Trans. Geol. Soc. Glasgow*, XIV, pt. 3, 1913, p. 247.

2. Analcite-basanite, lava flow, R. Ayr, 1 mile E. of Stair, Ayrshire. Anal. W. H. Herdsman.

B. Olivine-basalt, Craiglockhart type, near Redside, East Lothian. Anal. E. G. Radley. Quoted from The Geology of East Lothian, *Mem. Geol. Surv. Scotland*, 1910, p. 121.

C. Analcite-basalt, plug in volcanic vent, Calton Hill, Derbyshire. Anal. S. I. Tomkeieff.[2]

2. *Analcite-basanite.*

The rocks of this group have exactly the same mineral composition and textures as those of the foregoing group. They contain numerous microphenocrysts of olivine, which are often fresh, occasionally also augite, embedded in an intergranular groundmass of augite, felspar, iron ores, and analcite. Their main distinction from the olivine-basalts of Dalmeny type rests on the greater abundance of analcite, which in them ranks as an essential constituent. In accordance with the nomenclature of similarly-constituted rocks containing nepheline or leucite in place of analcite, these types are designated *analcite-basanite*. Some of the more felspathic varieties do not materially differ from some of the rocks described in the foregoing section, except that they contain a somewhat greater proportion of analcite. Many of the rocks, however, especially those from Stair, are much richer in the mafic constituents than the Dalmeny basalts, and appear to be practically identical with the Hillhouse basalt type from the Lower Carboniferous of the Midland Valley of Scotland,

ation-products such as calcite, haematite, are counted with the mafic or femic group of minerals. Furthermore the salic or felsic minerals form a much more definite group than the femic or mafic minerals, and their amount can be obtained with somewhat greater precision. In fact, when the norm is employed, the correct amount of the mafic group can only be obtained by deducting the total of the felsic group from 100. For the same reasons the felsicity is the best variable on which to base certain kinds of variation-diagrams (see Tyrrell, *Principles of Petrology*, 1926, p. 134 *et seq.*).

[1] *Mem. Geol. Surv. Scotland*, The Geology of the Glasgow District, Revised Ed., 1925, p. 178.

[2] Dr. Tomkeieff has been kind enough to assent to the publication of this analysis in advance of his own work.

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which also contains some analcite in the groundmass.[1] Small olivine-nodules and segregations of augite occur in some of these lavas.

The analysed rock (Table I, 2) from the exposures in the Ayr valley, one mile east of Stair, shows very abundant microphenocrysts of fresh olivine, in a groundmass composed of granules of augite, and slender plagioclase microlites in subordinate amount, enveloped in a pervading base of turbid analcite. Ragged crystals of iron ore (titaniferous?) are more abundant than is usual in these rocks, and reach a number and size only inferior to the olivine.

Analcite-basanite lavas occur abundantly in the valley of the R. Ayr east of Stair; Trabboch Burn; Tarbolton; Barnweill; and Mauchline Hill. As fragments in the vent agglomerates they occur at Raith Hill, Coylton; Craigs of Kyle; Polnessan Glen; Thornton House, Kilmaurs; Spy Knowe, and Greenhill, Waterside. They are especially abundant in the vent of Broom Hill, 2½ miles N.N.E. of Patna.

The *chemical composition* of the analcite-basanites is illustrated by an analysis of the Stair example set out in Table I, 2. It is there compared with the analysis of a Craiglockhart basalt from East Lothian, and with an analcite-basalt from a Lower Carboniferous vent in Derbyshire. Comparison with the analyses of the nepheline-basalt of Ashentree Glen, and the typical Hillhouse basalt of the Bathgate Hills (Table II, 3 and D), shows that the Stair analcite-basanite also has close affinities with these rocks. The Hillhouse basalt is obviously slightly richer in mafic minerals but poorer in analcite (and/or nepheline) than the Stair rock, as is shown by its lower silica, alumina, and alkalies, and by its norm (Table III, *cf.* col. 2 and col. D).

3. *Analcite-basalt* (*or monchiquite lava*), *nepheline-basalt, and limburgite.*

When felspar is reduced to insignificant proportions or is totally absent from these basic alkaline lavas, we arrive at the types analcite-basalt (sometimes called monchiquite lava), nepheline-basalt, and limburgite, according to whether analcite, nepheline, or glass represents the subordinate alkaline and felsic component. In hand-specimens these rocks are most often dark in colour,

[1] *Mem. Geol. Surv. Scotland*, The Geology of the Glasgow District, Revised Ed., 1925, p. 178.

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compact, dense, and heavy, occasionally showing scattered streaks and spots of whitish analcite. In thin section it is found that nearly all these rocks contain a pervading base of analcite; but when nepheline is also identifiable in notable amount the term nepheline-basalt has been used for them; and when there is a notable amount of interstitial, microlitic, brown glass, the term limburgite has been applied. The term analcite-basalt has been reserved for rocks in which neither nepheline nor glass has been identified in appreciable amount. It is also therefore used for somewhat altered rocks, which may have contained nepheline or glass, from which these constituents, sometimes also analcite, have disappeared by weathering. These rocks, in fact, might be treated under one heading, as similar rocks are in the *Glasgow Memoir* (Revised Ed., 1925, p. 178), where augite-monchiquites, nepheline-basalts, and limburgites are dealt with in the same section, and are described as containing numerous small phenocrysts of olivine and purple augite in a felspar-free base rich in microlitic augite and magnetite, and with interstitial analcite, nepheline, or glass. This description closely fits the rocks dealt with here.

*Analcite-basalt* is best represented by a beautifully fresh lava from the burn near Stevenston, 2/3rds. of a mile N.E. of Ochiltree. In thin section this rock is seen to consist of a crowded mass of small euhedral crystals of purplish augite, and sparse grains of magnetite, embedded in a scanty base of analcite. Olivine is very abundant in small euhedral phenocrysts, partly fresh, partly altered to a bright-red serpentine. One or two small phenocrysts of augite also occur. Besides forming the base of the rock, analcite is also found segregated into a few areas free from coloured minerals. These areas tend to be rounded and to have augite prisms aligned tangentially around their margins. Radial outgrowths of colourless, straight-extinguishing zeolite grow from the margins into these areas. Cubic cleavage is well marked in some of the larger patches, and the analcite shows anomalous double refraction very similar to that of leucite.

Fresh material of the same characters is found as blocks in the R. Ayr at Howford Bridge, and as fragments in the agglomerate of the Broom Hill vent, 2½ miles N.N.E. of Patna. Somewhat altered rocks of like character occur in the Sorn Hill, Polnessan Burn, and Polbaith Burn (Galston) vents.

Perhaps the most typical *nepheline-basalt* occurs as fragments in a vent exposed in the R. Irvine near Hurlford. In thin section

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this rock is seen to consist predominantly of shapeless granules of purple augite, and uniformly-scattered, minute grains of magnetite, in an apparently continuous, colourless groundmass. In polarised light this groundmass breaks up into laths of plagioclase, isotropic analcite, and low-polarising nepheline. The two last-named minerals occur in interstitial areas, in which the nepheline occupies the margins, and projects with good crystal form into the more or less altered analcite in the central parts. The nepheline also forms small plates poikilitically enclosing augite and felspar crystals. Phenocrystic olivine occurs abundantly as carbonate pseudomorphs, also augite as single crystals or as small polysomatic aggregates. There are a few small rounded vesicles filled with analcite. With the exception of the olivine phenocrysts the rock is perfectly fresh. Apatite needles are abundant.

A rock very similar to the above occurs in the Alton Burn, Tarbolton. It is, however, richer in nepheline, poorer in analcite and felspar, than the Hurlford rock, and carries numerous small flakes of biotite in the groundmass. This rock is also characterised by abundant apatite, which occurs in large stumpy crystals averaging 1/10 mm. in diameter, as well as in innumerable fine needles enclosed in the analcite.

The analysed rock, which forms a plug in the vent of Ashentree Glen, 3 miles N.E. of Patna (see p. 262), is similar to the two above-described rocks, but is of finer grain, and the nepheline it undoubtedly contains is not so clearly identifiable. It carries numerous xenoliths of a coarse fresh ultrabasic rock, consisting predominantly of olivine, a pale-green or pale-brown monoclinic pyroxene, colourless enstatite, and small but numerous anhedral crystals of brown spinel (picotite). This rock is a lherzolite, and compares well with the carbonated xenoliths of lherzolite which occur in the vent of the Heads of Ayr. It is of interest to recall that in or near this vent there occur several small plugs and dykes of analcite-nepheline-basalt very similar to that of the Ashentree Glen vent, one of which enclosed a xenolith of tolerably fresh lherzolite.[1]

A similar nepheline-basalt occurs on the edge of a small vent at Stevenston, Ochiltree; but it is not clear whether this rock represents a fragment within the agglomerate, or whether it is part of a hardened lava skin on the edge of the funnel.

[1] G. W. Tyrrell, Igneous Geology of the Ayrshire Coast from Doonfoot to the Heads of Ayr. *Trans. Geol. Soc. Glasgow*, XVI, pt. 3, 1918, pp. 339-63. See especially pp. 348-52; 357-9.

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*Chemical Composition.* The analysis of the nepheline-basalt of Ashentree Glen is given in Table II, 3. Compared with the analyses of the Sorn Hill Dalmeny basalt, and the analcite-basanite of Stair, it shows lower silica and alumina, but only slightly lower alkalies, with considerably augmented ferrous iron oxide and magnesia, indicating that it is at once richer in mafic minerals, and slightly more alkaline, than those rocks. The same point is brought out by the consideration of the norms, and the C.I.P.W. symbols of the three rocks (p. 279). The analysis also compares well with that of the nepheline-basalt of Whitelaw Hill, East Lothian (Table II, E) and less closely with that of Hillhouse basalt of the Bathgate Hills (Table II, D). Amongst the coarser intrusive rocks of the same age-suite its nearest analogue is the kylite of Benbeoch (Table II, F); that rock, however, is much richer in magnesia, and slightly poorer in alkalies, than the nepheline-basalts. It might be regarded as derived from a magma similar to that of the nepheline-basalts by the subsidence and accumulation of the early-formed olivine crystals.

TABLE II.

| | 3 | D | E | F |
|---|---|---|---|---|
| $SiO_2$ .. .. .. | 42.52 | 42.49 | 40.2 | 44.18 |
| $Al_2O_3$ .. .. .. | 12.90 | 13.85 | 12.8 | 10.67 |
| $Fe_2O_3$ .. .. .. | 1.53 | 2.59 | 4.0 | .97 |
| FeO .. .. .. | 10.71 | 9.32 | 10.4 | 10.03 |
| MgO .. .. .. | 13.53 | 11.21 | 11.9 | 17.77 |
| CaO .. .. .. | 10.55 | 9.76 | 10.4 | 9.75 |
| $Na_2O$ .. .. .. | 3.04 | 2.39 | 2.7 | 2.37 |
| $K_2O$ .. .. .. | 1.03 | .87 | .8 | 1.23 |
| $H_2O+$ .. .. .. | 1.25 | 3.35 | 3.4 | .97 |
| $H_2O-$ .. .. .. | .40 | .47 | | |
| $TiO_2$ .. .. .. | 2.08 | 2.51 | 2.9 | 1.30 |
| $P_2O_5$ .. .. .. | .39 | .61 | – | .38 |
| MnO .. .. .. | tr. | .29 | – | – |
| $CO_2$ .. .. .. | tr. | .22 | – | tr. |
| S .. .. .. | nil | – | – | – |
| (Ni, Co)O .. .. | nil | .09 | – | – |
| (Ba, Sr)O .. .. | – | .04 | – | – |
| | 99.93 | 100.06 | 99.5 | 99.62 |

3. Nepheline-basalt, plug in New Red Sandstone volcanic vent, Ashentree Glen, 3 miles N.E. of Patna, Ayrshire. Anal. W. H. Herdsman.

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D. Olivine-basalt (Hillhouse type), Hillhouse Quarry, Bathgate Hills, West Lothian. Anal. E. G. Radley. Quoted from The Geology of the Glasgow District, Revised Ed. *Mem. Geol. Surv. Scotl.* 1925, p. 174.

E. Nepheline-basalt, Chester's Quarry, Whitelaw Hill, East Lothian. Anal. J. H. Player. Quoted from, F. H. Hatch, *Trans. Roy. Soc. Edin.* XXXVII, 1895, p. 106.

F. Kylite, Benbeoch, Dalmellington, Ayrshire, Anal. K. Dittrich. Quoted from G. W. Tyrrell, *Geol. Mag.*, 1912, p. 122.

*General Mineral and Chemical Characters of the New Red Sandstone Lavas.*

The table of norms (Table III, 1, 2 and 3) shows the calculated mineral compositions of the three lavas that have been analysed, and they are there compared with the norms of the other rocks the analyses of which appear in Tables I and II. The norms in Table III are numbered and lettered in accordance with the analyses in Tables I and II.

TABLE III.

| | 1 | A | 2 | B | C | 3 | D | E |
|---|---|---|---|---|---|---|---|---|
| Orthoclase .. | 10.0 | 6.1 | 7.2 | 6.1 | 7.8 | 6.1 | 5.6 | 5.0 |
| Albite .. | 16.2 | 30.1 | 8.9 | 22.0 | 10.0 | 2.6 | 13.1 | 3.4 |
| Anorthite .. | 25.9 | 20.9 | 21.7 | 23.9 | 25.6 | 18.4 | 23.9 | 20.0 |
| Nepheline .. | 5.4 | 1.0 | 11.1 | .3 | 7.4 | 12.5 | 4.0 | 10.7 |
| Diopside .. | 18.1 | 14.5 | 21.6 | 17.9 | 21.6 | 25.1 | 17.0 | 25.0 |
| Olivine .. | 4.9 | 7.0 | 20.5 | 18.4 | 16.1 | 26.5 | 22.5 | 20.6 |
| Magnetite .. | 5.8 | 8.3 | 2.3 | 5.6 | 5.6 | 2.1 | 3.7 | 5.8 |
| Ilmenite .. | 3.8 | 5.2 | 3.6 | 3.8 | 3.8 | 3.9 | 4.7 | 5.5 |
| Haematite .. | 4.2 | 3.0 | – | – | – | – | – | – |
| Apatite .. | .7 | 1.3 | .7 | 1.0 | – | 1.0 | 1.3 | – |
| Calcite .. | 2.5 | – | – | – | – | – | – | – |
| Felsicity .. | 57.5 | 58.1 | 48.9 | 52.3 | 50.8 | 39.6 | 46.6 | 39.1 |
| C. I. P. W. Symbols.[1] | 'III. | (II) III. | III. | III. | III. | III(IV). | III. | III.' |
| | 5(6). | 5L. | 6. | 5L. | (5)6. | 6". | 5" | 6. |
| | 3". | 3. | 3. | 3(4). | 3". | 3. | (3)4. | 3". |
| | 4. | 4(5). | 4. | 4. | 4. | 4. | 4. | 4". |

[1] An addition has been made to the C.I.P.W. symbols by subjoining the letter L (=Lenad) to denote when a norm falling centrally in the 5th order (second item of formula) nevertheless contains a small quantity of felspathoid. Similarly the letter Q prefixed to the figure 5 denotes the presence of a small amount of quartz.



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The norms of these rocks give practically the actual mineral composition, if the nepheline be regarded as being partly or wholly displaced by analcite; *i.e.* the modes are essentially normative. The table shows that the felsicity decreases from 57.7 in the Dalmeny basalt to 39.6 in the nepheline-basalt, while the analcite-basanite occupies an intermediate position in this respect. The amount of nepheline increases in the same direction while the total felspar decreases; at the same time the plagioclase becomes richer in the anorthite component. These facts are illustrated by the variation diagram, Fig. 31, in which felsicity is plotted along the abscissa, and the proportions of the various felsic constituents along the ordinate. The curves for the felspars are almost straight lines, but the curve for nepheline flattens out considerably on approaching the mafic end of the abscissa. It is to be ob-

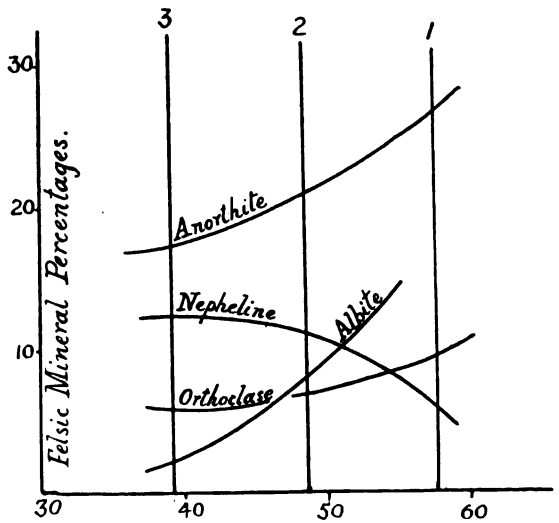


Fig. 31.

served that the actual silica percentages of these rocks would be quite useless in a comparison of this kind, and that the felsicity provides a much better index of variation. The progression shown by the norms is also clearly exhibited in the symbols denoting the position of the analyses in the American Quantitative Classification (C.I.P.W. symbols).

1. Olivine-basalt (*cf.* Dalmeny basalt), "III. 5(6). 3". 4.
2. Analcite-basanite, III. 6. 3. 4.
3. Nepheline-basalt, III (IV) 6". 3. 4.

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The symbols in the first two columns indicate respectively increasing richness in mafic (or femic) minerals, and increasing alkalinity. The relations of alkalies to lime, and of potash to soda, shown respectively in the third and fourth columns, remain practically the same throughout.

With regard to general chemical relations, the analyses of the Sorn Hill Dalmeny basalt and the analcite-basanite of Stair closely resemble that of the average nepheline-basanite as computed by Daly.[1] The latter, however, is slightly richer in soda and in potash than the Ayrshire rocks. The nepheline-basalt of Ashentree Glen closely resembles the average limburgite,[2] and less closely the average nepheline-basalt.[3] The latter is richer in alkalies, although possessing a smaller silica percentage, than the Scottish examples.

Compared with the products of Carboniferous igneous activity the New Red Sandstone lavas are in general at once more basic and more alkaline. Mineralogically expressed, they contain more of the mafic minerals, less of the felspars, but proportionately larger amounts of analcite and nepheline, than the majority of the Carboniferous basalts. Further, the more felsic lava types, such as mugearites, trachyandesites, trachytes, and felsites, which are now known to comprise a comparatively large part of the Carboniferous suite, have no known counterparts amongst the New Red Sandstone lavas.

B. Bekinkinite, teschenite, camptonite, crinanite, essexite (or theralite), and monchiquite, of the Carskeoch, Carclout, and Keirs Hill vents.

Of these types, found as intrusives in the agglomerate and neighbouring rocks of three vents in the Patna district, all save the essexite (or theralite) and crinanite, appear to represent varying facies of one and the same original magma; the remaining two are possibly derived from a somewhat different magma.

Bekinkinite, teschenite, and camptonite, form the central intrusive mass of the Carskeoch vent (see p. 263), while monchiquite forms sills in the neighbouring sediments, and comprises a large portion of Keirs Hill. A crinanitic type ("Carskeoch essexite") also occurs on Carskeoch Hill; while a porphyritic essexite or theralite (luscladite) constitutes a small intrusive mass in the vent of Carclout Hill.

[1] Igneous Rocks and Their Origin, 1914, p. 31.
[2] *Ibid.*, p. 30. [3] *Ibid.*, p. 33.

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The bekinkinite, teschenite, and camptonite of Carskeoch Hill consist of the same group of minerals combined in different proportions in the different rocks, and with varying textures. These minerals are: olivine, almost invariably serpentinised; a pale, patchily-coloured titanaugite; red-brown barkevikitic hornblende; ilmenite; plagioclase felspar; alkali-felspar; analcite and/or nepheline; and apatite.

The *bekinkinite* type represents the melanocratic assemblage in which the coloured minerals are decidedly more abundant than the colourless. In thin section, it shows sporadic olivine crystals altered to green serpentine, with abundant plates and granules of titanaugite, often segregated into patches resembling pyroxene nodules. The larger detached crystals are often invested by red-brown barkevikite crystals, especially where they happen to be adjacent to areas rich in the alkaline residuum. This amphibolisation, which is extensive in places, giving rise to complete, but irregularly-bounded barkevikite crystals containing small fragments of the original pyroxene, is clearly due to reaction-effects between the pyroxenes and the alkaline residuum of the magma.

A feature of the Carskeoch bekinkinite is the presence of fine-grained patches consisting largely of minute augite granules intermingled with a little felspar and analcite, and enclosing a few sporadic crystals of barkevikite and serpentinised olivine. These patches are capriciously distributed, and pass rapidly into the coarser normal rock. They somewhat resemble the ultrabasic types of lava above-described (ankaramite, etc.). There are also one or two patches consisting largely of tiny barkevikite crystals embedded in a base of felspar and analcite, which closely resemble the camptonite described below. Ilmenite occurs abundantly in the bekinkinite, mostly as skeletal crystals which are partly or wholly enclosed in, and present euhedral faces to, barkevikite and titanaugite, and even to the serpentinised olivine.

The felsic base in which these coloured minerals are set consists mainly of plagioclase felspar which, in some of the slides, forms zonary plates and comparatively large laths, in others a mass of small, well-shaped crystals with an almost basaltic texture and habit. The composition varies from oligoclase-andesine to acid labradorite. The plagioclase is mingled with some untwinned alkali-felspar, and interstitial turbid analcite. Occasionally the latter mineral forms large irregular masses occupying spaces which have been corroded out of the surrounding mineral mesh,

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regardless of the composition of its constituents. Apatite needles are conspicuous wherever analcite is abundant. Nepheline has been somewhat doubtfully identified in the analcite areas with much the same habit as described for the nepheline-bearing lavas.

These rocks conform closely to the definition of bekinkinite proposed by A. Lacroix.[1] They represent the melanocratic facies of the teschenite group, especially those teschenites which are rich in hornblende. Amongst Scottish rocks the Carskeoch bekinkinite closely resembles the well-known rock of Barshaw near Paisley.[2] Judged by the analysed rock, however (see Table IV), it is somewhat richer in felspars, but poorer in analcite and coloured minerals than the Barshaw type.

The *teschenites* of Carskeoch differ from the bekinkinites chiefly in the greater abundance of analcite and felspars that they display. The reaction phenomena between augite and analcite resulting in the production of barkevikite and also biotite, are remarkably well developed in these rocks. This is unquestionably due to the abundance of analcite and alkali-felspars indicating the presence of a water- and alkali-rich liquid residuum at the end-stage of the crystallisation process. To these reaction effects must also be ascribed the widespread analcitisation of the plagioclase. An abundance of late-formed needles and crystals of apatite testifies to the presence of phosphorus and lime in the late magmatic residuum.

These hornblende-teschenites closely resemble some of the Lugar types;[3] and the resemblance is heightened by the occurrence of veins and patches rich in analcite and barkevikite, which compare with *lugarite*. Other veins and patches, however, exhibit a concentration of analcite and alkali-felspar, and thus more closely compare with the analcite-syenite veins which occur in the Glasgow and Charlestown (Fife) teschenites.[4]

Another variation in the direction of finer grain and panidiomorphic texture, with a concomitant dwindling in the amount of analcite and alkali-felspar, so that a rock of lamprophyric type, consisting essentially of barkevikite, titanaugite, and labradorite, is produced, leads to the appearance of *camptonite* in the Carskeoch

[1] *Comptes Rendus*, Paris. clxx, 1920, p. 20. Also see *Min. de Madagascar*, 1922, ii, p. 637.

[2] G. W. Tyrrell, *Geol. Mag.*, 1915, pp. 304-11; 361-6.

[3] G. W. Tyrrell, *Q.J.G.S.*, LXXII, pt. 2, 1917, pp. 84-129.

[4] F. Walker, *Geol. Mag.*, LXIII, 1926, pp. 343-7.

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complex. Camptonite is extensively developed as veins, but also as larger masses, which pass gradually into the coarser bekinkinites and hornblende-teschenites by increase in the amount of analcite. One vein on the northern flank of the hill is nepheline-bearing. Another mass of camptonite, near the summit of the hill, shows the segregation of barkevikite crystals into patches where it is associated with plagioclase and a little analcite. These patches are enveloped in a ground-mass of basaltic type rich in iron ore, which latter mineral is not found in the amphibole-rich patches. Apatite in relatively large columnar crystals is abundant in this rock.

The very fresh rock which forms a supposed ring-dyke in the Carskeoch vent (see p. 265, and Fig. 29) was called essexite of Carskeoch type in my former paper.[1] Megascopically it is light-grey, compact, and fine-grained. In thin section it is seen to consist of fluxionally-arranged plagioclase laths ($Ab_1An_1$), the interstices between the crystals being filled with nearly colourless augite and fresh olivine. Here and there minute angular interspaces are filled with isotropic matter, the form and arrangement of the fragments of which suggest the former presence of nepheline. A few broad plates of pale augite and crystals of olivine interrupt the general trachytoid fabric. Ilmenite and biotite occur sparsely, and a little orthoclase may be detected on the margins of the plagioclase laths, extending thence irregularly into the interspaces. This rock appears to come nearest to the crinanite type of intrusion, and is therefore called crinanite, but it is by no means a typical member of this group. It does not agree well with any known intrusive mass belonging to the same period of igneous activity in Scotland.

The intrusion of the Carclout vent has been described as a porphyritic essexite allied to the Crawfordjohn and Lennoxtown rocks.[2] It is, however, comparatively rich in nepheline, and might equally well be classed as a theralite. Lacroix, indeed, has relegated the Crawfordjohn example to that group of theralites which he calls *luscladite*, a type of olivine-theralite characterised by containing little or no hornblende.[3]

In hand specimens the Carclout rock is greyish, compact, finegrained, and carries numerous lustrous black phenocrysts of

[1] *Geol. Mag.*, (V), IX, 1912, p. 120.
[2] *Ibid.*, p. 121.
[3] *Comptes Rendus*, Paris, clxx, 1920, p. 21.

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augite up to ½-inch in width. Microscopically it is composed of a mesh of broad laths of plagioclase ($Ab_1An_1$), which are idiomorphic to abundant and often beautifully-fresh nepheline. Clear analcite occupies some of the interspaces, and encloses the euhedral terminations of felspar laths. Titaniferous magnetite is aggregated into groups of euhedral crystals associated with flakes of biotite. In the above, as groundmass, numerous large phenocrysts of deep purple titanaugite and fresh olivine are set. The pyroxene moulds and encloses olivine, and occasionally also the terminations of the felspars. Apatite occurs in great abundance as needles and small crystals enclosed in nepheline and analcite.

Dr. A. Scott, when describing the allied rock of Crawfordjohn, carried through a quantitative mineral determination of the Carclout luscladite.[1] The mode was found to be as follows: plagioclase ($Ab_1An_1$) and orthoclase, 35.2; nepheline, analcite, and a little unidentified turbid matter, 15.0; titanaugite, 34.5; olivine, 9.7; biotite, and a little hornblende, 1.5; ilmenite, 3.7; and apatite, 0.4 per cent. The Crawfordjohn rock was found to contain about twice as much olivine as that of Carclout, but was otherwise closely similar. Hence Lacroix's term luscladite, applied to the rock of Crawfordjohn, may also be fittingly applied to that of the Carclout intrusion.

The *monchiquites* of the region under consideration occur as irregular protrusions into the vents, and also as sills and dykes in the surrounding country rocks. It is believed that they occasionally represent chilled facies of the more basic and ultrabasic alkalic intrusions, such as the bekinkinites and kylites. Megascopically they are dark-grey to black, compact, basalt-like rocks, with an occasional white spot of analcite, and a green spot of serpentinised olivine. They often contain large xenocrysts of hornblende, augite, and alkali-felspar;[2] and abundant xenoliths of ultrabasic rocks closely resembling the lherzolite blocks of the vent-agglomerates, as well as numerous inclusions of the shales and sandstones that constitute the country rocks.

In thin section these rocks are seen to be made up predominantly of a finegrained holocrystalline groundmass consisting of minute, euhedral granules of augite and iron ores, in a turbid, isotropic base which, in places, is clear enough to show the usual

[1] *Geol. Mag.*, (VI), II, 1915, p. 458.

[2] V. A. Eyles, *Geol. Mag.*, LXI, 1924, p. 474.

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characters of analcite. This mineral also fills a number of small spherical or irregularly-shaped cavities. In some areas relatively poor in augite, small flakes of biotite appear; and these are often grouped around clusters of iron ore granules, as if due to reaction between them and the analcitic base. In this groundmass are scattered numerous microphenocrysts of olivine and augite, microphenocrysts or xenocrysts (it is not quite certain which) of alkali-felspar, xenocrysts of brown spinel and calcite both derived from the disintegration of lherzolite xenoliths which are occasionally abundant. Enormous xenocrysts of titanaugite and barkevikite can be obtained locally in the monchiquites ,as, for example, on the eastern side of Carskeoch Hill.

The olivine, which is often perfectly euhedral, is invariably altered to bright-green serpentine. The augite is an almost colourless variety, sometimes euhedral, at other times anhedral, or showing irregular outgrowths into the groundmass. Almost always the crystals have spongy cores which give a different extinction angle to the homogeneous outer parts. They are occasionally thickly sown with minute granules of iron ore, and shot through with thin flakes of biotite. The alkali-felspar is very sporadic in its distribution; frequently it exhibits irregular hexagonal outlines, but shows no signs of twinning. It is often partly or wholly replaced by calcite. The mineral is almost certainly the anorthoclase recorded by Eyles (*op. cit.*), but the fragments are too scattered and small, and often too much altered, to subject to detailed microscopical examination.

The large xenocrysts of titanaugite and barkevikite do not differ in any essentials from the minerals of like nature which have been described above (p. 282). As a rule they can be distinguished in thin section by means of a broad external zone of corrosion in which magnetite has been developed, and by their large sizes. One or two minute, sharp-angled fragments of brown spinel (picotite) with broad, deep-black edges, occur in each slide. These, along with irregular masses of calcite, have been derived from the numerous xenoliths of lherzolite which occur in the monchiquites. These rocks are identical with those that have formerly been described (p. 277, and Tyrrell, 1920, p. 348). Some of these fragments, however, seem to have been close to pure olivine-rocks, as pseudomorphs after pyroxenes are occasionally much less abundant than in the above-described examples.

Many xenoliths of the country-rocks, mostly black shale and

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sandstone, are enclosed in the monchiquites; and this is particularly the case with the Keirs Hill exposure. Some of the smaller shale xenoliths appear to have suffered a kind of magmatic transfusion, whereby granules of iron ore have been deposited along their planes of fissility, and flakes of biotite have grown through their substance.

The monchiquitic rocks here described obviously have close mineralogical and chemical similarities to the nepheline- and analcite-basalts dealt with above (p. 275).

The chemical composition of the rocks treated in this section is illustrated in Table IV, where an analysis of the Carskeoch bekinkinite (col. 4) is compared with the Barshaw (Paisley) bekinkinite (col. G). The Carskeoch rock is distinctly richer in potash and silica, but poorer in magnesia and lime, than that of Barshaw, corresponding to its somewhat greater felsicity. The Carskeoch bekinkinite also shows chemical affinities to the Dalmeny basalt of Sorn Hill (Table I, 1), the crinanite of Howford Bridge, Mauchline (Tyrrell, 1923, p. 254), the teschenite of Cathcart (Glasgow),[1] and the picrite-teschenite of Blackburn (Bathgate).[2]

TABLE IV.

| | 4 | G | 5 | H | I | J |
|---|---|---|---|---|---|---|
| $SiO_2$ .. .. | 44.50 | 40.87 | 46.4 | 45.03 | 40.79 | 40.25 |
| $Al_2O_3$ .. .. | 14.55 | 16.23 | 16.4 | 14.82 | 15.54 | 13.07 |
| $Fe_2O_3$ .. .. | 3.64 | 1.31 | 1.6 | 2.77 | 3.90 | 5.81 |
| FeO .. .. | 8.30 | 7.37 | 6.9 | 8.71 | 9.48 | 7.24 |
| MgO .. .. | 7.61 | 9.83 | 9.0 | 7.79 | 8.61 | 8.07 |
| CaO .. .. | 9.90 | 11.13 | 8.2 | 9.83 | 12.71 | 11.55 |
| $Na_2O$ .. .. | 2.86 | 2.78 | 5.6 | 4.33 | 3.44 | 2.73 |
| $K_2O$ .. .. | 1.80 | .53 | 2.0 | 1.51 | 2.05 | 2.61 |
| $H_2O+$ .. .. | 2.95 | 4.28 | .4 | 1.71 | .60 | 1.20 |
| $H_2O-$ .. .. | .40 | 1.35 | | .24 | .58 | 1.50 |
| $TiO_2$ .. .. | 2.12 | 2.85 | 3.5 | 2.30 | 1.79 | 2.70 |
| $P_2O_5$ .. .. | .39 | .52 | .2 | .58 | .47 | .62 |
| MnO .. .. | .08 | .64 | – | .37 | .20 | .32 |
| $CO_2$ .. .. | .80 | .38 | – | .22 | nil | 2.14 |
| S .. .. .. | .12 | – | – | – | – | tr. |
| (Ni, Co)O .. | nil | .06 | – | – | – | – |
| (Ba, Sr)O .. | – | nil | – | – | tr. | – |
| $FeS_2$ .. .. | – | .21 | – | – | – | – |
| | 100.02 | 100.34 | 100.2 | 100.21 | 100.16 | 99.81 |

[1] The Geology of the Glasgow District, *Mem. Geol. Surv.* 1925, p. 170.

[2] The Geology of the Neighbourhood of Edinburgh, *Mem. Geol. Surv. Scotland*, 1910, p. 299.

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4. Bekinkinite, intrusion in volcanic vent, Carskeoch Hill, Patna, Ayrshire. Anal. W. H. Herdsman.

G. Bekinkinite, intrusion, Barshaw, near Paisley (Renfrewshire). Anal. E. G. Radley. Quoted from the *Glasgow Memoir*, 1925, p. 174.

5. Porphyritic essexite or theralite (luscladite), Carclout, near Patna, Ayrshire. Computed from mode given by A. Scott, *Geol. Mag.* (vi), II, 1915, p. 458.

H. Porphyritic essexite, Lennoxtown, Stirlingshire. Anal. E. G. Radley Quoted from the *Glasgow Memoir*, 1925, p. 170.

I. Monchiquite, marginal facies of luscladite of Craighead (Crawfordjohn), Lanarkshire. Anal. A. Scott. Quoted from A. Scott, *op. cit. supra*, p. 514.

J. Monchiquite, Tertiary dyke, Port nan Gadan, Losset, Kintyre, Argyllshire. Anal. W. H. Herdsman. Quoted from W. J. McCallien, *Trans. Geol. Soc. Glasgow*, XVIII, pt. 1, 1927, p. 109.

From Dr. A. Scott's quantitative mineral determination of the Carclout luscladite it is possible to compute its approximate chemical composition by utilising Scott's analysis of the Crawfordjohn titanaugite, and of an average olivine calculated from the normative olivines of the Lennoxtown and Crawfordjohn luscladites, and the Carskeoch and Barshaw bekinkinites.

Further it was assumed that nepheline and analcite were present to the amounts of 10 per cent. and 5 per cent. respectively and that orthoclase comprised 10 per cent. of the total rock. The result of the computation is given in col. 5 of Table IV. It compares well with the Lennoxtown rock (col. H), but less well with the Craighead (Crawfordjohn) example. The analysis runs very close to that of the average theralite,[1] but is richer in MgO, and slightly more soda-rich in relation to potash.

No analysis of the monchiquites of this district is as yet available, but the opinion may be hazarded that their chemical composition will be found to be closely akin to that of the nepheline- and analcite-basalts. In Table IV, 1, an analysis of the monchiquitic marginal facies of the Craighead (Crawfordjohn) luscladite is given, a rock which is mineralogically closely similar to the rocks under consideration. A recently-published analysis of a Kainozoic (?) monchiquite from Kintyre is tabulated along with it. The resemblance between the analyses is very close, but the Kintyre rock shows approximate equality in the amounts of soda and potash, while the Craighead rock is more sodic.

C. Agglomerates and tuffs, with their contained fragments other than basaltic lavas.

[1] Tyrrell, *Principles of Petrology*, 1926, p. 117.

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The coarse fragmental material due to explosive action which fills the New Red Sandstone vents will be termed *agglomerate* irrespective of its composition. The great bulk of the infilling material consists of basaltic lava; hence the term *volcanic agglomerate* may be fittingly applied. Howell Williams[1] restricts the term agglomerate to contemporaneously-formed, coarse, pyroclastic rocks, consisting mainly of large, rounded or subangular fragments. When the material is localised within a vent he used the term *vent-agglomerate*. The term *volcanic breccia* is applied by him to similar material of angular shape; and he also includes under this heading the non-contemporaneous breccias due to dry avalanches within a crater (*e.g.* Vesuvius), and breccias due to the erosion and re-assortment of coarse angular ejecta. The distinction between rounded or subangular, and angular, fragments, however, is not significant enough to warrant more than one name for coarse ejected material of contemporaneous origin due to explosive action; and the term agglomerate will therefore be used in this paper for all coarse material within the vents irrespective of whether the fragments are rounded or angular.

The agglomeratic filling of volcanic vents may be derived as follows:—

1. Explosive disintegration of molten lava filling a vent. This gives rise to fine glassy dust, pumiceous and vesicular glassy lapilli, and bombs of glassy or semi-glassy constitution with or without bread-crust surfaces or concentric structures.

2. Material derived from the walls of the vent, or from a previous solid infilling, by explosive disintegration (contemporaneous), or by avalanching in the crater subsequent to an eruptive period (non-contemporaneous). The fragments may be of all sizes from large blocks to the finest dust. In regard to composition a distinction may be made between, (*a*) *cognate*[2] material, consisting of lava fragments erupted within the same cycle of igneous activity; and (*b*) *accidental* material, consisting of foreign igneous, sedimentary, or metamorphic rock fragments derived from the country-rocks.

[1] Notes on the Characters and Classification of Pyroclastic Rocks. *Proc. Liverpool Geol. Soc.*, XIV, 1926, pp. 223-48.

[2] See use of terms 'cognate' and 'accessory cognate' in regard to lapilli by H. Williams (*postea* p. 291).

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3. Material derived from great depth, which may likewise be cognate or accidental. These fragments may be termed *intratelluric*. As examples of cognate intratelluric material may be cited the lherzolite and other ultrabasic rock fragments in many of the West of Scotland vents of Carboniferous and New Red Sandstone age (Tyrrell, 1920, pp. 357-9), and the eclogites, etc., of the Kimberley diamond pipes.

The term agglomerate will be thus applied to coarse pyroclastic material formed in and around volcanic foci by explosive disintegration, or by avalanche action subsequent to explosion. The term volcanic breccia will be applied to material (mostly angular) resulting from the general shattering of country rock by volcanic activity,[1] to accumulations of talus on the flanks of volcanic cones, to the products of mud-flows, and to pyroclastic material re-distributed by erosive action not long subsequent to its formation.

The lower limit of size for the fragments of agglomeratic material may be taken as one inch, since Howell Williams defines the next smallest grade-size of fragments as *lapilli*, which range between ¼-inch and 1 inch in average diameter.[2]

The infillings of the New Red Sandstone volcanic vents of Ayrshire generally consist of agglomerate as defined above. Fragments ranging from blocks several feet in diameter down to pieces about 1 inch in diameter constitute the bulk of the material. These fragments are embedded in a relatively scanty matrix, consisting of numerous lapilli in a base of minutely-comminuted rock matter. The larger blocks consist mainly of previously-consolidated lavas, which have been described along with the actual lava-flows in an earlier section of this paper. They thus constitute the *accessory cognate* coarse material in Howell Williams' sense. True *cognate* material, *i.e.* bombs due to ejection of molten lava, has not been found; although a great many of the fragments of lapilli size consist of vesicular glassy basalts which have no doubt originated in this way.

Relatively few of the larger blocks consist of sedimentary material derived from the walls of the vents. Patna Hill, however, contains a large number of blocks of black shale, as well as a few

[1] Tyrrell. Geology of Arran. Chapter xiv. *Mem. Geol. Surv. Scotland.* In the press.

[2] *Op. cit.*, p. 231.

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of quartzite, and a finegrained silty greywacke. Baked sandstones and quartzites, and one block of crinoidal limestone, were found in the Carclout vent. Very large boulders of quartzite, sandstone, and shale, occur in the vent of Keirs Hill; and huge boulders of red and white sandstone are to be found on the eastern side of the little vent in Polnessan Glen.

In several vents, especially those which cluster around Patna, there occur numerous blocks and cobbles of carbonated lherzolite (p. 263). These rocks are of intratelluric origin, and are also found as xenoliths in nepheline-basalt and monchiquite intrusions in the vents (p. 277). They usually weather a light-grey or whitish colour, and are often sub-rounded due to solution effects. In the Patna Hill vents there were observed pebbles of a very friable rock consisting almost entirely of biotite. This rock seems to be similar to the *biotitite* described by H. S. Washington from an Italian volcanic focus.[1]

The matrix in which the coarse materials are embedded consists of angular lapilli and broken crystals, in a base of finely comminuted rock dust. Howell Williams defines lapilli as fragmental volcanic ejecta between ¼-inch and 1 inch in diameter, irrespective of whether they are derived from contemporary igneous material or from foreign sources.[2] *Cognate* lapilli consist of fresh magma which fell as lava drops. *Accessory cognate* lapilli are fragments derived from previously consolidated lavas erupted in the same cycle of igneous activity. Fragments of country-rocks derived from the walls of the vents are called *accidental* lapilli. The nomenclature might be extended to include *intratelluric* lapilli derived from plutonic depth.

Generally speaking the matrix of the New Red Sandstone vent-agglomerates consists of cognate lapilli, accessory cognate lapilli, accidental lapilli, and intratelluric lapilli, in the order of abundance as given. The base is simply finely-broken material of the same nature. There is, of course, considerable variation in the relative amounts of these constituents. Many of the rock are almost pure cognate lapilli tuffs with little or no sedimentary material; others, on the contrary, are rich in fragments of sand-

[1] The Italite Locality of Villa Senni. *Amer. Journ. Sci.* (5), 14, 1927, p. 187.

[2] *Op. cit.*, p. 231.

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stone, shale, and grains of quartz, and pass into tuffaceous sandstones. With increase in the amount of sedimentary material a notable degree of stratification often becomes apparent. While many of the tuffs contain large numbers of separated crystals, in none of them are the crystals so preponderant as to constitute crystal-tuffs in Pirsson's sense. They are all, therefore, lithic tuffs.[1]

The cognate lapilli form angular to sub-rounded fragments of basaltic glass or cryptocrystalline basalt, brownish in colour when fresh, green when more or less decomposed, but often darkened by clouds of iron ore particles. In general they are highly vesicular, the vesicles often being perfectly spherical, but occasionally they are drawn out into tubes by flow. The accessory cognate lapilli are merely angular fragments of the various basaltic lavas which have been described above. They have been produced by the explosive disintegration of already consolidated lava, the structures and textures of which had been determined before ejection. Some of the vents are characterised by particular types of lava fragments. The majority contain fragments of the Dalmeny basalt type; the Carclout vent contains a great abundance of a Dalmeny basalt type characterised by porphyritic augite (p. 272). The vent of Broom Hill is notable for the abundance of fragments of analcite-basanite lava (p. 275).

Intratelluric lapilli, consisting of carbonated lherzolite, are found in small quantity in practically every vent-agglomerate, but they are most abundant in the vents of the Patna district. Accidental lapilli are not abundant in the matrices of the agglomerates. They are represented by chips of the adjacent shales, small fragments of sandstone, and very occasionally a fragment of limestone.

The vents of Dunston Hill and Carline Knowe, 2 and 3 miles respectively to the N.E. of Patna, contain large masses of a finegrained, almost silty, sandstone, some carrying large, rough scoriaceous lapilli, others full of decomposed basaltic lava debris. These may be interpreted as accumulations of sand within the vents, derived from the crumbling of sandstone walls into which scoriaceous fragments, lapilli, and volcanic ash, were dropped by small intermittent explosions.

[1] L. V. Pirsson. The Microscopical Characters of Volcanic Tuffs. *Amer. Journ. Sci.*, (4), 40, 1915, pp. 191-211.

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The chief crystal constituents of the tuffs consist of quartz and felspar derived from the disintegration of the Carboniferous sandstones which mostly form the walls of the vents. These grains are in general sharply angular; only a few have the corners and angles rounded off. Round and polished grains are comparatively rare even in the tuffaceous sandstones overlying the lavas in the Ballochmyle section on the R. Ayr, or in the Lugar Water and Dippol Burn sections near Ochiltree. The general rarity of rounded and wind-polished grains may be taken to indicate that the eruptions ceased not long after the beginning of deposition of the desert sandstones which occupy the Mauchline—Tarbolton basin.

Fragments of fresh and serpentinised olivine, and of augite, derived from the basaltic lavas, are fairly common in the tuffs; grains and aggregates of calcite, and small angular chips of brown spinel, derived from the lherzolite fragments, occur in many of the slides. The spinel fragments have the peculiarity that they are invariably surrounded by a narrow zone of fibrous green serpentine. Fragments of pale-brown hornblende occur in one of the Carclout slides.

The ultimate base in which all the above-described constituents are embedded consists of finely-broken crystals and glass, derived from the explosive comminution of the solid rocks within and bordering the vents, and from the explosive disintegration of molten lava. It is mostly somewhat decomposed, with the development of green serpentinous and chloritic minerals, and dark or reddish ferruginous products. The base is comparatively fresh, however, in one of the Carclout specimens. Occasionally calcite fills up interspaces in the tuffs; but in a tuff matrix from the Barnweill vent, Tarbolton, irregular cavities are filled with euhedral crystals of analcite.

The abundance of fragments of previously-consolidated lavas, and of crystals derived from those lavas, even in the agglomerate of vents remote from the existing lava outcrop surrounding the Mauchline-Tarbolton basin, suggests a much more extensive former covering of New Red Sandstone basalts over the region of Central Ayrshire, extending northwards as far as Stevenston, and southwards to Dalmellington.

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## No. XI.—The Pitchstone Porphyry of Penrioch, Arran.

By P. J. Robinson, A.M.Inst.C.E.

(Read Nov. 10, 1927. Issued 1st September, 1928).

This Pitchstone, which is noted in the list of Arran pitchstones given in the Geological Survey Memoir (1903, p. 91) but which has not hitherto been described in detail, is exposed, for a few yards only, on the hillside about half a mile N.E. of Penrioch Farm, at the extreme south end of a prominent scarp marking the line of a fault. It is intruded into the ring of schistose rocks which surround the Northern Granite. The junction between the pitchstone and schist is not a sharp one the pitchstone having penetrated along joints in the schist and included blocks up to a foot in diameter. It is not clear from the field evidence whether the intrusion is a sill or a dyke, but it is probably the latter.

In the hand specimen, the rock is a glossy, black pitchstone showing abundant large and conspicuous phenocrysts of felspar, smaller ones of quartz, and numerous xenoliths of a basaltic rock of aphanitic texture, hardly to be distinguished, macroscopically, from the schistose country rock. The fracture is splintery and uneven and the rock breaks up in diverse directions owing to the numerous cooling cracks which have developed. In thin section the rock is seen to consist of a base of pale yellowish brown glass, mottled a deeper brown in patches and crowded with minute microlites, which carries large phenocrysts of felspar and quartz and abundant microphenocrysts of pyroxene. The great majority of the microlites are of a ferromagnesian mineral, but occasionally felspar in this form occurs; magnetite is a minor constituent and there are also a few sporadic crystals of brown tourmaline.

The quartz phenocrysts are abundant and a few attain a size of 6 m.m. Some show good crystal faces with the corners merely rounded off by corrosion; others, on the contrary, are much corroded, and have quite lost their crystal form, embayments of the glassy base frequently extending deep into the heart of the crystal.



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They almost all carry small inclusions and negative crystals of pale brown glass, quite free from microlites, but often with an included bubble. A few of the quartz phenocrysts are surrounded by a " reaction rim " of granular pyroxene.

Within the glassy base, adjacent to and sweeping round the boundaries of the quartz phenocrysts, are fine, hair-like, concentric lines; these, in ordinary light, are of a pale green colour, but under crossed nicols show as bright lines. It seems probable that they are perlitic cracks (1903, pp. 122-123), caused by contraction on cooling, which have afterwards become infiltered with a doubly refracting substance.

It may be noted that the lines sometimes turn into the edge of a phenocryst where they register with cracks extending across the quartz. Whilst they invariably occur round the quartz, they do not make their appearance round the felspar.

The felspar phenocrysts, some of which attain a size of 10 m.m. are all of plagioclase, but two varieties of this are represented. The majority of the larger ones are unstriated oligoclase about An:20, the remainder showing albite twinning, sometimes combined with that on the pericline law, are Andesine, about An:33.

Certain of the felspars showing both albite and pericline twinning have crystallised in complicated skeletal forms which occur not only individually but also as outgrowths on the oligoclase phenocrysts. It seems probable that these were formed at a late period in the history of the intrusion when the viscosity of the magma had been considerably increased by cooling, the skeletal forms indicating an impaired freedom of molecular transference.

Some of the phenocrysts are much corroded, veins and indentations of the groundmass penetrating deeply. Negative crystals and strings of glodulitic inclusions of glass are frequent; inclusions of pyroxene also occur.

In addition to absorbtion, softening and mechanical factors seem to have played a part. The edges of a number of the phenocrysts have been rendered dusty and turbid, apparently by the softening of the felspar and by its having been split up along its cleavage planes into very minute rhombs; some of the smaller phenocrysts have been attacked throughout in this manner. The pyroxene microphenocrysts occur as irregular grains and also as well developed eumorphic crystals. They are pale green in colour and are faintly pleochroic indicating a soda bearing variety

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of augite. It seems almost certain that a rhombic pyroxene (enstatite) is also present, as straight extinction together with faint pleochroism in pale green and pale red is given in a number of cases. Owing to the paucity of suitable basal sections, a conclusive determinative in convergent light has not, however, been obtained. Magnetite occuring as inclusions and intergrowths, is frequently associated with the pyroxene. The ferromagnesian microlites which crowd the glassy base are pale green in colour. They may be either augite or hornblende, their minute size precluding differentiation between these two minerals. The majority occur as very fine lath shaped sections, with ragged and somewhat pointed ends, arranged in pairs crossing each other in the shape of the letter X. Single lath shaped sections, sometimes with swallow tail terminations form the minority; plumose and arborescent forms, so frequently found in the pitchstones from other localities in Arran, are absent.

Each microlite is surrounded by an area of nearly colourless glass. The glass filling what may be termed the interspatial areas between these influence zones is of a darker brown in colour and, consequently, the base has a mottled appearance and is in places banded, the lighter bands being due to the fact that there the microlites are more tightly packed together. Under a high power, certain areas of the glass are seen to carry numerous very minute opaque globulites.

Stream line flow is very clearly shown round the edges of some of the larger phenocrysts, the microlites being arranged with their long axis parallel with the edges of the phenocrysts.

This, together with the resorbtion, shows that the macrophenocrysts solidified under plutonic conditions prior to extrusion, and they might be termed more correctly cognate xenocrysts.

The xenoliths of the " basaltic " rock enclosed in the pitchstone shew, in their section, a few scattered microphenocrysts of basic labradorite and augite, in a groundmass composed of slender laths of acid labradorite, about An:50, grains and narrow elongated crystals of augite and enstatite in approximately equal amount, numerous cubes and rod shaped microlites of magnetite, and an abundant interstitial glass, which is clear and almost colourless. The pyroxenes are in greater quantity than the felspars.

There are a few very minute patches of greenish alteration products but otherwise, owing no doubt to the sealing effect of its enclosure in the pitchstone, the rock is remarkably fresh.

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The augite is very pale brownish yellow in colour and is non-pleochroic. The enstatite, as in Cumbraite from the type locality (1917, p. 308), is frequently intergrown with augite in a characteristic manner, occurring as a central core flanked with parallel growths of augite on either side.

In addition, the rock carries xenocrysts of quartz and felspar. The former are in all cases surrounded with a reaction rim of granular pyroxene. The felspars are dusty and turbid but usually have a narrow rim of clear felspar. They appear to be of the same composition as the macroporphyritic felspars of the Pitchstone and there seems to be no doubt that the Xenocrysts in the " basalt " and the large phenocrysts in the Pitchstone have a common origin. The rock from which the basic xenoliths have been derived must have solidified prior to the pitchstone intrusion, and it seems probable that the latter represents the acid facies of a composite intrusion, the basic member of which is not here exposed at the surface but is only represented by the xenoliths.

Composite intrusions of Pitchstone and " Augite Andesite " have been noted elsewhere in Arran at various localities (1893). Whilst the rock here described might be classed provisionally as an Augite Andesite, the fact that the felspars are Labradorite and not Andesine suggests that it might be classed more properly as a Tholeeite of subacid type.

The most acid end members of the Tholeeite series of the West of Scotland as defined by Tyrrell (1917, p. 355) are the Leidleites and Inninmorites of Mull (1916, pp. 205-217). The Arran rock has many points of resemblance to Leidleite and only differs from it mineralogically in the presence of enstatite and in the occurrence of microphenocrysts of augite. A close examination was made of these, as the related Inninmorite carries small microphenocrysts of a peculiar uniaxial variety of augite; they, however, all proved to be biaxial.

Returning now to a point noted in the description of the Pitchstone, viz., the occurrence of reaction rims of pyroxene round some of the quartz phenocrysts. This is unusual for this type of rock. They have been noted by Smellie (1913, pp. 121-139), in the Quartz Porphyry of the composite sill at the south end of Bute, which in part has solidified as a Pitchstone Porphyry, and ascribed by him to the basification of the acid magma by the assimilation of basic Xenoliths.

A similar cause may have been in operation here but, if so, the

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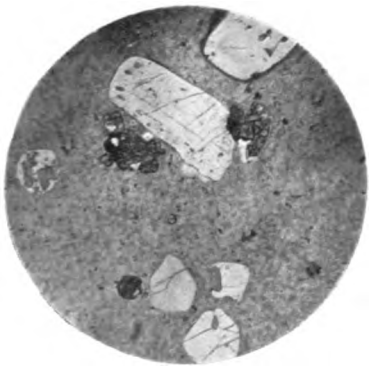

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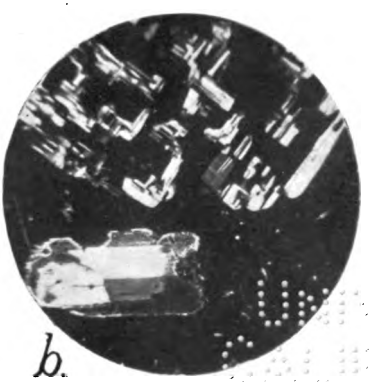
c.



b.

PHOTOMICROGRAPHS OF THE PITCHSTONE OF PENRIOCH, ARRAN.

(a). Showing phenocrysts of Felspar, Quartz and Augite. Ordinary light. X 15.

(b). Showing late formed phenocrysts of Felspar which has crystallised in skeletal form. X 20. Crossed nicols.

(c). Xenolith of basic rock enclosed in pitchstone, showing xenocrysts of quartz with reaction rims of granular pyroxene and microphenocryt of felspar. Ordinary light. X 20.

*Photographs by D. M. Filshill.*

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basification must have been extremely local, as the rims do not appear round groups of adjacent quartz crystals, but only in isolated instances.

An alternative origin is possible for these. The quartz crystals, with the envelope of pyroxene attached, may have been liberated by solution from the basic rock and caught up in the pitchstone magma during extrusion.

In conclusion, I have to acknowledge the kind help afforded me by Dr. G. W. Tyrrell, who checked the mineral determinations and supplied references and copies of papers.

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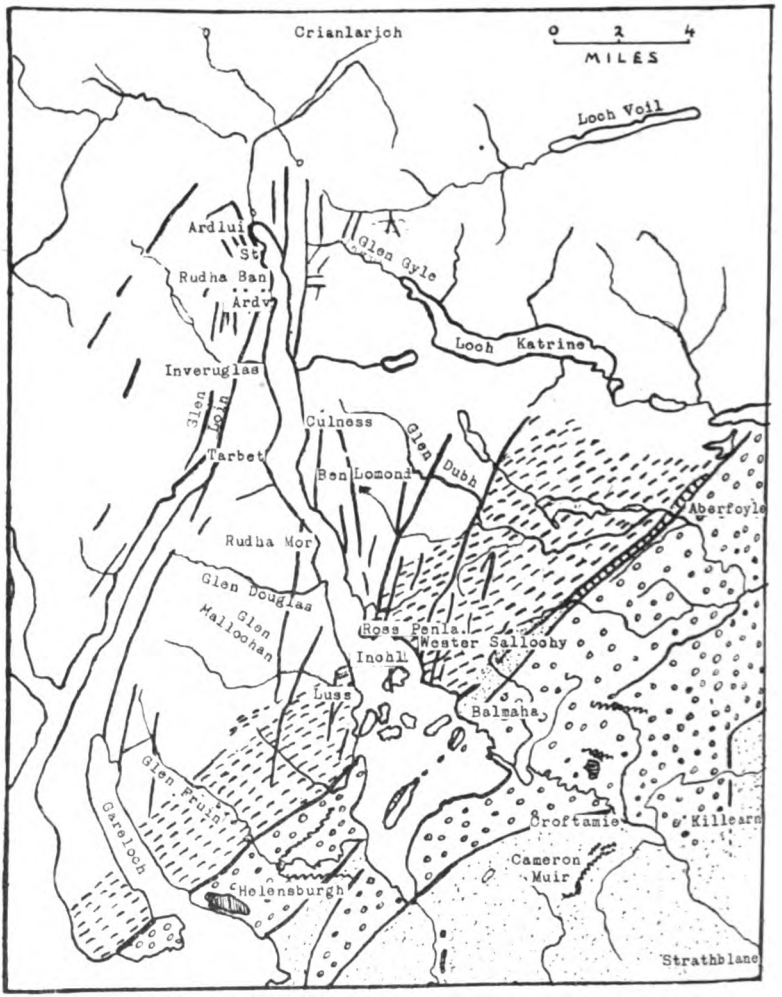


*Ardv.* = Ardvoirloin.
*Inchl.* = Inchlonaig.
*St.* = Stockindroin.
——— = Faults.

Moraines. ~~~~

Upper Old Red Sandstone.
Lower Old Red Sandstone.
Highland Border Series.
Lennoxian.
Dalradian.

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## No. XII.—The Geology of Loch Lomond.

By J. W. Gregory, D.Sc., F.R.S., University of Glasgow.

(Read 9th February, 1928; issued 1st September, 1928).

The advent of the British Association recalls the absence of any general account of the geology of Loch Lomond, although it is one of the most attractive features in the Glasgow district. It is the largest lake in Britain (length 21 miles; breadth ½-¾ mile at the northern end, and 4½ miles at the southern; mean breadth 1¼ miles: area 27½ sq. miles); it is the third deepest (623 ft., when its surface level was 23.9 ft.), and its floor descends 600 ft. below sea level. Its scenery is unsurpassed among British lakes, from the contrast between the grandeur of the upper part, which has the typical features of a fiord, and the picturesque incidents of its southern end, which has the sinuous shores, gently sloping banks, many headlands and islands of a fiord. McCulloch has declared (1824, vol. I, pp. 209, 210) "Loch Lomond is unquestionably the pride of our lakes; incomparable in its beauty as in its dimensions, exceeding all others in variety as it does in extent and splendour, and uniting in itself every style of scenery which is found in the other lakes of the Highlands. . . . .As, with regard to the superiority of Loch Lomond to all the other lakes, there can be no question, so, in the highly contrasted characters of its upper and lower portions, it offers points of comparison with the whole; with all those at least which possess any picturesque beauty; for it has no blank." Its epithet of "The Queen of Scottish Lochs" is fully justified.

The contrast in geographical character between the two ends of Loch Lomond depends upon its geological structure. The loch traverses obliquely three series of rocks. The northern end is in gneiss, mica-schists, and schistose quartzites which have been grouped as the Loch Lomond Series. South of Luss on the western coast, and of the Ross Peninsula on the eastern, lies a broad band of non-schistose rocks—slates, grits and conglomerates—which are cut off abruptly to the S. by the Highland Boundary Fault. That fault forks on the eastern side of Loch

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Lomond; the northern branch is the main line of the fault, but is here the less conspicuous. It passes through Arrochymore Point, Shantron Hill and Ardencaple, and behind Rosneath Point to Kilcreggan. The southern and younger branch passes through Balmaha, Inchcaillach and Inchmurrin, to the south-western shore of Loch Lomond near Arden, and, throwing the Calciferous Sandstone against the Lower Old Red Sandstone, it reaches the Clyde near Craigendoran. The Boundary Fault in the main separates the older rocks from the Old Red Sandstone, which is broken through by the stumps of the old volcano of Duncryne. Lower Carboniferous sediments form the hills between Arden and Helensburgh, and Carboniferous lavas form the conspicuous plateaus of the Kilpatrick Hills and Campsie Fells.

## I. The Rocks of the Basin.

1. *Old Red Sandstone.* Most visitors approach the loch from the S., and the first rocks seen belong to the Old Red Sandstone, which forms some gently undulating drift covered plains. The Lower Old Red Sandstone consists of coarse red to purplish sandstones with, especially along the northern margin, conglomerates and boulder beds. Some of the boulders are so large that a glacial origin has been suggested for them. The beds resemble torrential wash swept by floods of water out of mountain gorges and spread over the plains in broad delta-fans. The rivers, between the floods, would flow across the plains, in irregular shifting channels, like the " shingle rivers " of New Zealand; the stones were then worn and polished by wind-blown sand.

The Lower Old Red Sandstone conglomerates may be seen from the steamer beside Balmaha Pier, where they are steeply tilted by the Highland Boundary Fault. They rise eastward as the conspicuous purplish ridge of Conic Hill. Upon its slopes many of the boulders and pebbles have been cracked and smashed, and some of them have been broken into slices and the segments displaced and recemented The pebbles are mostly quartzites derived from the older rocks to the north. A detailed study of them should show what members of the Dalradian Series outcropped in the basins of these Old Red Sandstone rivers.

The Upper Old Red Sandstone consists of soft clayey and calcareous sandstones which were once red, but in most of the exposures have been bleached into gray, buff, or green. They are usually horizontal or have a gentle dip. North of the Boun-

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dary Fault they rest directly on the older rocks; although they have suffered some displacement by later movements along that Fault, they are clearly younger than its main dislocation. These beds contain some impure limestone or cementstone, and they pass up conformably into the lower beds of the Carboniferous. The gradual passage between the two systems explains why the Geological Survey map, sheet 30, issued in 1878, calls the Upper Old Red Sandstone the Calciferous Sandstone Series, a term now reserved for the Lower Carboniferous.

2. *The Highland Border Series—Ordovician.* A yellowish band may be seen from the steamer on the northern side of Conic Hill a little below the crest. It is a limestone formed along the Boundary Fault. For three miles further E.N.E. graptolitic slates, radiolarian cherts, graphitic shales, grits and fossiliferous limestones occur along this fault and continue from the Kelty Water to beyond Aberfoyle. Professor Jehu and Dr. Campbell (1917), discovered in this Highland Boundary Series graptolites and brachiopods which indicate its Ordovician age. The cherts are similar to those of the Arenig Beds of the Southern Uplands, and this series represents the overlap of the Ordovician Sea against the Highlands.

3. *The Loch Lomond Series and the Lennoxian.* The classification of the rocks to the north of this Highland Border Series has given rise to long controversy which is still rife. There is no need to follow in detail the earlier views as they have been well summarized by Professor MacNair (1908, Vol. I, pp. 26-51). James Nicol in his Geology of Scotland (1844, p. 149) and in his paper on the Southern Grampians (1863), which is characterised by his usual insight, showed that the northern part of Loch Lomond traverses metamorphic rocks which have an average strike from W.S.W. to E.N.E. They are therefore cut across obliquely both by Loch Lomond and by the Highland Boundary Fault, which in this part of its course trends N.E. Nicol showed that the metamorphic rocks form an anticline, being horizontal or gently inclined across the middle of the loch, and dipping S.S.E., on the southern side and N.N.W. on the northern side. Nicol also recognised that the rocks are most altered along the centre of this anticline, the slates and grits of Luss and the Pass of Leny representing a much lower grade of metamorphism than the gneisses at the northern end of Loch Lomond. This fact has been fully confirmed, as by Cunningham-Craig (1904), and Dr.

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C. E. Tilley (1925). Nicol regarded the oldest beds as being exposed at the axis of the anticline, with a steadily ascending series to the N.N.W., and S.S.E. The interpretation advanced by Mr. Cunningham-Craig and adopted by the Geological Survey map, sheet 38, is contrary to that of Nicol. No " Explanation " of that sheet has been issued, but the conclusions of the surveyors are stated in the Summary of Progress of the Geological Survey for 1899 (1900, pp. 36-8, 165-6) and 1900 (1901, pp. 138-9), in Sir Archibald Geikie's Presidential Address to the Geological Society (1901), and Mr. Cunningham-Craig's paper (1904). The chief conclusion is the reversal of Nicol's sequence and the claim that there is an ascending series through the slates of the Highland Border Series, and the grits and slates of Luss and Aberfoyle to the schists through them to the gneisses at the northern end of Loch Lomond. Rocks which have yielded graptolites and brachiopods were claimed as the oldest in Scotland ! This conclusion had to be modified on the discovery of the fossils by Professor Jehu and Dr. Campbell; but it was still maintained for the rest of the series, and there was claimed to be an ascending series from the grits and slates at Luss northward to the Moine gneiss.

The rocks must be inverted either on Loch Lomond or near Callender. Nicol held that the original position has been retained at Loch Lomond; and this view is supported by the beds there showing less signs of disturbance, the dips being gentler and more regular through wider belts, and the slates being less shattered, so that they have been extensively quarried, whereas near Callender they are so broken as to be commercially of no value. Mr. Cunningham-Craig's valuable account of the petrography shows that the most intensely altered rocks, the albite-gneisses on the western shore of Loch Lomond are near the northern end, between Inveruglas and Stuckindroin, and that the gneisses pass southward into schistose quartzites. I differ mainly from Mr. Cunningham-Craig, by doubting the further transition from the schists to the Luss slates, grits and conglomerates.

Mr. Cunningham-Craig calls the rocks from the Green Beds of Ardlui and the gneisses to the schistose grits at Luss the Ben Ledi Group. As the typical rock is albite-gneiss, which has not been described on Ben Ledi where the characteristic rock is a conglomerate of which the relations are dubious, and as the best sequence of these rocks is that along Loch Lomond, the term Loch Lomond Series appears more appropriate. This series is part of

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the Dalradian System, while the Luss Slates, and their associated grits I regard as part of a later division, intermediate between the Blair Atholl Series and the Torridonian; and as it is well developed in the district of Lennox, it may be called the Lennoxian.

Traverses from the Highland Boundary Fault show that the Lennoxian slates and grits are succeeded northward by schists, which become more and more altered and pass into gneiss. This succession gives the impression of a continuous passage from the slates by increasing metamorphism into gneiss, as held by Sir Archibald Geikie and Mr. Cunningham-Craig. The succession has however proved deceptive as regards the supposed passage from the Ordovician slates and cherts through the Aberfoyle Slates and grits to the schists; and the passage from the slates to the schists appears also invalid. The critical area for settlement of the relations of the grits and slates to the schists is along the northern border of the band of slate, which has been worked on both sides of the Gareloch, at Luss, near Ross Point S. of Rowardennan, and at Aberfoyle. The junction of the slates and schists is often obscure and drift covered. It occurs W. of Loch Lomond to the N. of Luss, and on the eastern side near Rowardennan.

Near Luss the slates are interbedded with grits and quartz-felspar conglomerates, of which two examples have been described by Mr. Cunningham-Craig. The Leny Grit at Craignahullie, on the main road, ¾ mile S. of Luss Hotel, he describes (1904, 16, 28, pl. II, f. i), as containing pebbles of granulitic quartz and a large quartz pebble in a "schistose but non-crystalline" matrix. It seems to be a quartz-breccia in which the matrix has been cleaved by pressure, but is non-crystalline. A finer grit from Creachan Hill (2¼ miles S.W. of Luss) contains ragged pebbles of granulitic quartz, decomposed felspar, and a little chlorite and sericite, which may be partly of clastic origin.

These descriptions confirm my experience of these rocks as slates and grits which have been subjected to sufficient pressure to produce cleavage, strain effects, occasionally some marginal granulation of the quartz pebbles, and some chlorite and sericite; the larger micas and chlorites, the altered felspars, the granulitic quartzite, and the fragments of schists, are derived from the older rocks to the N.

The slates continue northward from Luss along the Tarbet road through Row Wood. A little N. of the 13th milestone is an exposure of slate, felspathic quartzite and non-schistose quartz-

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felspar breccia; the rock is crushed and irregular. Then follows a long low exposure of chloritic schistose-quartzite; further on beyond Dun Mor, a stream gives a good exposure, 100 ft. above the road, of schistose-quartzite in parallel laminae, one-eighth to a quarter of an inch thick. Thence northward the rocks are increasingly more crystalline, and the fragmentary material becomes gradually destroyed and recrystalized.

At Craigentuie a good selection of rocks from the cliff above is laid out on a delta fan; the predominant rock of the road outcrops is the chloritic schistose-quartzite; it is well exposed at the quarry at the 15th milestone in a 30 ft. dyke that Dr. Tyrrell has identified as Malchite, which contains many baked inclusions of schist.

A quarry S. of the Douglas delta is worked in a schistose-quartzite with eyes of quartz, with some apparent false-bedding due to flow under pressure. The folia are coarse and the aspect gneissose. Some original grains of felspar and hornblende are still recognizable. It has abundant authigenous chlorite.

N. of Glen Douglas the first rocks that outcrop by the road are cut through by horizontal thrust-faults; some bands have a second foliation and some show slip-strain foliation; many of the quartz-blows and veins were formed during the movement, for some of them have been moved, while others were formed after the rock had come to rest. The rock above the thrust-planes has been moved northward. Further corrugated and faulted exposures occur half a mile further N. At Rudha Mor recent road widening has given a good exposure of the biotite quartzitic schist, which, though with clear signs of origin from a grit, retains few of the clastic constituents. Further N., as Mr. Cunningham-Craig has shown, there is a gradual incoming and increase of albite to the albite-gneiss of the northern shores of the loch; this rock is well shown at Ardvoirlich, and I agree with Mr. Bailey (1923, p. 325; *cf.*, also two analyses by Dr. Pollard, 1904, p. 57), that it is an altered felspathic grit.

The same succession as that on the Luss-Tarbet road is exposed to the N. and N.W. of Luss. The rocks to the N. of the slate are chloritic-quartzitic schists and schistose-quartzites, which pass into schists with less clastic constituents remaining.

In Glen Mallochan some thin beds of chlorite-epidote grit are probably the attenuated continuation of the Green Beds of Sron Aonaich, on the southern slopes of Ben Lomond. These Green

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Beds have played an important part in the correlation of the Loch Lomond Series. They are well developed at Ardlui on the northern and on Ben Lomond at the southern side of the anticline. The true "Green Beds" are of clastic origin and are schistose chlorite-epidote grits. Their origin as volcanic ash has been suggested, but is unproved. Mr. Cunningham-Craig has included in the Green Beds some hornblende-schists which he remarks, it is "not easy to distinguish from hornblendic schists of igneous origin" (1904, p. 22). Some of them as near Ardlui are basic sills (Gregory, 1910, p. 6; Dr. A. Scott, 1915, p. 183), which must be distinguished from the clastic grits.[1] The Green Beds of Sron Aonaich are less well developed to the W., as N. of Rowardennan.

At Luss the Survey map (sheet 38) suggests an unconformity between the schists and slates; for a band of slate is shown separated by a strip of schist from the main slate-grit area to the S.

The map around Luss appears to me in most respects correct, but I am not convinced of the existence of the intermediate schist band;[2] for the rocks near the confluence of the Sron an Laoigh with the Allt Doran appear to be grit and slate unusually crushed by a fault. The Survey mapping, if correct, would be most easily explained by the slate band, which is represented at the western end as breaking into a series of tongues, being superposed on the schists. Whether this band of slate is an inlier due to an upfold, or is an infold, or an outlier, it is equally inconsistent with the view of a general increase in metamorphism northward. Why should this band have been left as slate, while the rock between it and the main slate area of Ben Ruisg has been altered into schist?

The sudden passage from the schists to the slates and grits is repeated on the eastern side of the loch, S. of Rowardennan. Half a mile S. of the hotel outcrop gritty quartz-chlorite-schists, and the Carraig ridge, a little further S., consists of a schistose-grit. On the shore S. of Ross Mill, the rocks are again fine-grained mica-schists and chloritic-quartz-schists, and some of the schists are greenish through the abundance of chlorite. The greenish quartz-chlorite-schists extend to Pilot Bay, where the

[1] This view is consistent with the description and analysis of one of the Ardlui Green Beds by Sir John Flett and Dr. Pollard (1904, pp. 57-8).

[2] This area would repay more detailed study and mapping on the six inch scale, especially as the area here has been complicated by several N. to S. faults which have thrown the beds out of line.

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northern headland includes mica-schist, with folia of granulitic quartz and felspars invaded by granulitic quartz.

The southern headland of Pilot Bay includes conglomerate, with pebbles of granular quartzite, 2-4 inches long, and pebbles of vein-quartz 4 inches long; the pebbles are unbroken, and the bed is interstratified with a band of cross-cleaved grit. These beds pass into the slates and quartz-felspar breccia of Ross Point. The slates in Ross Peninsula have been extensively worked. They are normal green and purple slates interbedded with gritty fragments. These rocks are non-schistose, though some layers have been crushed and cleaved, and some micaceous surfaces formed by slip-strain.

The junction of the slates and quartz-felspar breccia with the schists is close to the line marked on the Survey map as the junction of the "Schistose Grit" with the mica-schists. The conglomerate S. of Pilot Bay appears to be a basal conglomerate at the base of the slate-quartzite-grit and breccia series of Ross Peninsula; and as the conglomerates and breccias are composed of the debris of the schists to the N. the slates and grits were doubtless derived from the same source.

In the neighbourhood of Rowardennan, N. of the hotel, the rocks include schists, Green Beds and gneiss. Some of the quartzitic biotite-chlorite-schists show a double foliation; and some white mica schists are associated with phyllitic beds that have a well developed slip-strain cleavage. These rocks include albite-schist and regularly bedded biotite-gneiss with 16-20 folia to the inch. Some green bands of chloritic-quartzitic schist occur with a quartz-conglomerate near Sput and over Tom Eas, and in the Coire Corrach W. of the Sron Aonaich fault, to the E. of which are the typical massive Green Beds. Further S. on the Ben Lomond footpath N.E. of the hotel, the schists are of a less altered type and include gritty schists with distinct clastic grains in a matrix of mica and chlorite. The low hills between Rowardennan on the N., Cluan on the S., and the fault scarp to the E., consist of chloritic and biotitic schistose-quartzites, with inconspicuous felspar; some of the fine-grained bands appear phyllitic; some schistose breccias include blue quartz pebbles. The junction between the schists and slate is hidden by drift, as the quartz-felspar breccia of Ross Point outcrops at Dubh Lochan. This rock is associated with the slate which has been worked in a quarry at 350 ft. O.D., above Wester Sallochy; the

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slate strikes about E.N.E. and dips 60°-70° southward. Slate trial pits have been made further E. just above the level of 800 ft. N. of the slate is a band of the quartz-felsper breccia which outcrops in the Ross peninsula; this band tapers eastward till it is cut off by the fault that runs past the southern end of Loch Chon and reaches Loch Lomond 1½ miles N.W. of Balmaha. N. of this breccia the maps mark a broad sheet of the "Mica-Schist and undifferentiated schist" which is Mr. Cunningham-Craig's Ben Ledi Group.

In the hope of finding a junction I examined the ground from the stream above West Sallochy to the Caol Ghleann. The junction of the slate and "Schistose-Grits" is marked on the Geological Survey map along the upper part of the northern tributary of the stream through Sallochy Wood. The six inch map marks three parallel streams N. of the 820 ft. slate dump; the first is on slate; the second should be on the "schistose grit" with the junction between them. North of the 1st stream is a cleaved grit, like that which at the base of the Maol Dun carries galena in the joints. The second stream is on slate; and even the northernmost and largest of the three streams crosses, at about 900 ft., gritty slate and quartzite.

Creag Mhor (the 1269 ft. summit) also consists of cleaved quartzite, with inclusions of phyllite, and rock like that at Maol Dun. North of Creag Mhor is a grit with quartz pebbles. Further N. are wide slopes with rare exposures which, though in the band mapped as 'mica schist,' are of slate. The moraine hummocks consist mainly of slate debris. The best exposure I saw in this slope at N.E. by N. from Blairvockie Farm, in a stream bed (at 800 ft., beside the highest birch trees) was a normal slate. Thick bracken covered the ground and the next exposure seen was a chlorite-biotite-quartzitic schist in the cliffs of the Caol Ghleann.

Any traverse across the southern borders of the Highlands shows the succession of the slate-grit series, chloritic and schistose-quartzites, mica-schists, and gneiss. This fact apparently supports the impression of a continuous upward passage from slate to gneiss. Hence the claim that the slate-grit series does not pass into the schist-gneiss series must be tested at other localities. For example, at the Gareloch the sudden passage from the albite-gneiss and schist series to non-schistose grits and slates and quartz-felspar conglomerates was observed by the Society in one of its excursions.[1] The conglomerates here, as S. of Luss, include many

[1] *Trans. Geol. Soc. Glasg.*, vol. xiv, 1910, p. 83.

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grains of granulitic quartz and of felspar which is traversed by granulitic veins; and the granulitic structures had certainly been developed before these fragments were included in the conglomerates. The granulitic material is similar to that in the schists to the N. and is doubtless derived from them. Some of the later conglomerates of the grit-slate series include fragments of slates which inderlie them. Hence they also give evidence that the slate-grit series is younger than the schists. The conglomerates are well seen at the western end of Rhu (Row) railway station, where they include large lumps of slate.

North of Shandon a band of conglomerate crosses the hills from Glen Fruin Valley to the Gareloch and though its pebbles are not very distinctive, as the felspars have been destroyed they also probably came from the northern schists.

That the slate-grit series near Shandon rests uncomfortably on the schists is indicated by the occurrence of inliers of the schist exposed by the denudation of the slate.

Similar evidence might be quoted from the section from Aberfoyle past Loch Chon. Slates and grits, containing conglomerates full of fragments from the schists, rest on the schists, which pass from chloritic schistose-quartzites to mica-schists and gneiss.

It is unnecessary to deal here in detail with the evidence from other parts of Scotland as to the relations of the Dalradian and Lennoxian, which are in general much the same as at Loch Lomond. The gradual increase in metamorphism from the albite-gneisses of the axis of the Dalradian anticline southward into chloritic-mica-schists and schistose-quartzites is natural, since the gneisses are the older and were more deeply buried. In contrast to the gradual change from the gneiss to the schistose-quartzite (*i.e.*, from the lower to the upper parts of the Loch Lomond Series) is the sudden passage from the schists to the slate-grit series. The junction is often buried beneath drifts, and has been often obscured by the intense compression to which both series have been subjected; but the change is sudden compared with the gradual transitions in the Loch Lomond Series, and the uniformity in the slate-grit series to the south.

The rocks on both sides of the junction line are naturally similar in aspect, as the slates and grits are made up of the debris of the schists, and have been subjected to a sufficient pressure to cleave them, to give them the same strike as the schists, and in some places to produce sericite and chlorite. The

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coarser bands in the Lennoxian must be derived from the adjacent Dalradians, as they contain fragments of all the constituents of the schist series, including chlorite, mica, granulitic quartzite, and felspars traversed by granulitic veins; these minerals were certainly altered before their inclusion in the Lennoxian. The Lennoxian were not only post-Dalradian, but were later than the movements which altered the Dalradians into schist and granulitic quartzites.

The following classification summarizes the succession here suggested of the Pampalaeozoic or pre-Cambrian rocks of Loch Lomond.

| | |
|---|---|
| Lennoxian—Aberfoyle Series | Leny slate and grits. |
| | Quartz-felspar conglomerates and grits. |
| | Luss and Aberfoyle slates with some limestone bands. |
| | Quartzites and quartz-felspar conglomerate. |
| Dalradian—Loch Lomond Series | Chloritic schistose-quartzites and chloritic schist. |
| | Micaceous and chloritic schistose-grits. |
| | Green Beds. |
| | Albite-schist and gneiss. |

## II. The Evidence of the Dykes.

From the beginning of the Palaeozoic the only rocks and deposits in the area are the dykes, glacial deposits, and later drifts. The dykes include lamprophyre, malchite,[1] and quartz-dolerites which

[1] The dykes of the Loch Lomond basin have not been adequately investigated, and it would be a useful service to determine more fully their nature, age, and relations to the faulting, especially near the Dumbartonshire Ben Vorlich, and Ben Vane.

Dr. Tyrrell has kindly examined the rock of the 30 ft. dyke from the quarry, 2½ miles N. of Luss, and reports as follows:—"The principal constituent is oligoclase or oligoclase-andesine with a smaller proportion of orthoclase. Hornblende, entirely altered to chlorite, is the most prominent coloured constituent. The alteration has disengaged iron-ores which are scattered as minute particles in and around the chlorite pseudomorphs. In addition there is some original iron-ore which appears from its leuxocenic alteration to be titaniferous. It is associated with small shreds of bleached biotite. A little



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(as at Rowardennan and Glen Mallochan near Luss) are marked on the maps as basalt. Sir Archibald Geikie has drawn an important inference from the dykes. They cross the Loch Lomond basin near the summit of Ben Vorlich and over the mountains E. of the loch; and as he identified the dykes as Kainozoic, he inferred that the Loch Lomond valley was excavated after the Kainozoic volcanic period in Scotland. The lamprophyre and malchite dykes are Devonian and the quartz-dolerites probably Permian. I am not aware of any dyke in the Loch Lomond basin of Kainozoic age, and Dr. Tyrrell tells me that he knows of none. Some of the dykes have a N.W. to S.E. trend, which in western Scotland is characteristic of the Kainozoic; but they are near Ben Arthur (the Cobbler) and Ben Vane, and, being related to those intrusions, may also be Devonian. Nevertheless as other fiord valleys of Scotland are intersected by Kainozoic basaltic dykes, the valleys were doubtless excavated after the date of those dykes which are probably Miocene. As the Loch Lomond Valley obviously belongs to the fiord valley-system of western Scotland, it may be regarded as of Pliocene age, and certainly as pre-glacial.

## III. Glacial Geology.

The glacial deposits of the Loch Lomond basin are of great variety and interest, and in excellent preservation. The oldest glaciation was by an ice sheet that covered the whole country and even the highest summits. This glaciation moulded the hills, enlarged the valleys, swept away the loose material and deposited it in the glacial drifts of southern Scotland. The deposition of the older boulder clay of the Midland Valley was contemporary with the later stages of this glaciation. The Loch Lomond Valley was formed before it as the Clyde boulder clay contains abundant blocks of the Garabal Hill granite and occasional specimens of the Loch Tay Limestone probably from Ben Duchraig; and these rocks must have been carried through the valley.

quartz appears interstitially, filling up small spaces between the felspars. All constituents except iron-ores and quartz are markedly euhedral and the texture is therefore thoroughly panidiomorphic.

This rock seems to be *malchite*. It conforms well with the definition given in "Geology of Ben Nevis and Glencoe" (Mem. Geol. Surv., 1916, p. 156): "In them (*i.e.* the malchites) porphyritic felspars are either inconspicuous or absent, while the rocks themselves are of dioritic composition and of hypabyssal structure, with a marked tendency to panidiomorphism. The group is a wide one and includes many rocks previously classed as not-typical porphyrites or lamprophyres, or else as fine-grained diorites."

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The second glaciation was mainly in the valleys and around the higher mountains, and parts of the plateau were left uncovered. The Loch Fyne granite is littered with boulders due to weathering during this interval. A great glacier flowed down to Loch Lomond and at its southern end spread westward up Glen Fruin, where it deposited a well preserved moraine (Renwick and Gregory, 1907) and an eastern lobe reaches about the same height in the Endrick Valley. The glacier no doubt also passed through the Leven Valley to the Clyde. It does not appear to have gone much farther, for on Shantron Moor, on the northern side of Lower Glen Fruin, the moraine shows that the ice sloped from the level of 700 ft. to 300 ft., on a gradient south-westward of 1 in 25; and the gradient of the opposite lobe, as shown by the Cameron Muir moraine, is 1 in 26 eastward; the ice slope across the Glen Fruin lobe from Shantron Moor to 600 ft. on Benuchara Moor was about 1 in 130.

The representative of the Glen Fruin moraine on the eastern side of lower Loch Lomond is in fragments; it includes a mound at Shandon, north of Drymen, at 300 ft., and some less definite hummocks at High Wood (500 ft.), on the Gartmore Road (Renwick and Gregory, 1907, p. 52). The best remnant is on Cameron Muir, where it is shewn by hill shading on the Geological Survey Map (Sheet 30). It has all the characteristics of a moraine of the Loch Lomond Glacier in the Glen Fruin stage, including large erratics of contorted gneiss from the upper end of Loch Lomond—Miss Currie found a boulder about 4 ft. in diameter of Garabal granite—and it descends eastward from its highest point (540 ft.), where it bends sharply southward to cross the Cameron Burn, in a length of three quarters of a mile to 400 ft., at an average gradient of about 1 in 26.

The maximum extension of this glacier was probably about synchronous with the glaciation of the Southern Uplands which formed the low level moraines of Galloway, as at 225 ft. in the Cree Valley north of Newton Stewart and at 175 ft. at Southwick near Dalbeattie (Gregory, 1926, pp. 357-360)

The fragmentary nature of the terminal moraine of the Loch Lomond Glacier in the Endrick Valley and its absence from the Leven Valley are doubtless due to its destruction when the country subsided, the sea ran up the Leven Valley, and Loch Lomond became a fiord. The southern part of the valley was probably submerged up to the level of about 260 ft. O.D., the height of the shelly beds near Drymen.

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A reindeer antler was found at Croftamie (at 102 ft.), with marine shells beneath the Endrick boulder clay, and it was probably deposited close to the shore. It is scratched as by sand, but bears no glacial striae. The adjacent sands and clays with marine shells were described by R. L. Jack, (1875) as marine; but as the shells are rolled James Geikie and the Survey Memoir have adopted the view that they were redeposited in a glacial lake. The sea however has considerable powers of rolling, and the worn conditions of the shells is no proof of freshwater action. Hence at that time—which judging from the reindeer and shells was Upper Paleolithic—the sea probably reached the height of about 260 ft., in the Endrick Valley, while the Loch Lomond glacier still reached the islands in the loch. The land again rose till the sea sank to the level of about 100 ft.; and the clays with marine shells of the 100 ft., raised beach episode were laid down in many places along the sides of Loch Lomond, as far N. as the island of Inchlonaig. The recession of the ice allowed the sea to extend further N, than at the time of the Croftamie reindeer; but as Mr. Cunningham-Craig suggests (1900, p. 166), the glacier still occupied the northern end of the loch. At this time were being formed the moraines described by Anderson (1896), in the northern part of Loch Lomond at Rudha Ban. This further uplift and retreat of the sea accompanied the further withdrawal of the ice until the deposition of the moraines in Glen Falloch and those in the corries.

The glacial succession may be summarized as follows. 1. The oldest glaciation which covered the whole country and the higher peaks in the Loch Lomond district. 2. The deposition of the older boulder clay. 3. A later glaciation, during which a glacier that flowed down the Loch Lomond valley formed the moraine of Glen Fruin, and the fragmentary moraines of the Endrick Valley and Cameron Muir. 4. A subsidence by which the lower part of Loch Lomond Valley was entered by the sea and became a fiord. The Endrick Valley was submerged to the height of about 200 ft., indicated by the marine shells in the sands and boulder clay, and in the shell bed with the reindeer at Drymen Station. This date was Upper Paleolithic. 5. The fiord probably became more ice-littered, its water colder and muddier, and the Endrick boulder clay included fewer marine shells. The glacier had by this time probably receded to the middle of Loch Lomond, allowing the deposition of the Inchlonaig clay with shells (e.g. *Pecten islandicus*)

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now extinct in British seas. 6. The further recession of the ice and reduction of the submergence; and deposition of the successive moraines from Rudha Ban to Glen Falloch. 7. Further uplift and recession of the glaciers and the formation of small moraines on the highland and in the corries.

This sequence is different from that required by the explanation of the Drymen Sands by a glacial lake. According to J. Geikie (1894, p. 281) and the Geological Survey Memoir (1925, pp. 226-30) the extension of the Loch Lomond glacier which formed the Glen Fruin and Endrick moraines was after stage 6 in the above series. James Geikie states (1894, p. 279) that the Loch Lomond Glacier was later than the fiord stage, whereas I regard the Glen Fruin and Cameron Muir moraines as formed in stage 3, long before the marine shells were deposited in the 100 ft. clays of Loch Lomond or that loch had last become an arm of the sea.

## Tilting and Terraces.

The occurrence of various earth movements since the beginning of the glaciation raises the question whether there is any evidence by lake levels as to the tilting of the country. The steep slopes of drift beside the loch show many of the terraces known as " sheep tracks " which appear to be due to soil-slip. On my first passage up Loch Lomond my attention was attracted by a straight line like an old lake beach, with a slight slope southward. It runs from Wester Sallochy (two miles S. of Rowardennan), where it is at the level of 760 ft., for two miles southward. Less conspicuous terraces of the same kind occur a little higher. The terrace is less regular than it appears from the lake; it is a worn hummocky bank of morainic material, and its gradient represents that of the glacier margin. It is not a lake beach, and gives no evidence of the tilting of the area.

*Frost-packed Stone-Polygons.* Much attention has recently been called to the formation of ' stone-polygons ' as a minor feature of frost action (for example C. S. Elton, 1927, J. S. Huxley and N. E. Odell, 1924). A beautiful and remarkably varied illustration of this phenomenon may be seen among the old slate fragments on the southern shore of the Ross Peninsula.

*Evidence of the Loch Lomond Fauna.* The invasion of the sea during the fiord period would have destroyed the pre-glacial

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freshwater fauna in the loch; while the subsequent retreat of the sea and reoccupation of the loch by freshwater would have destroyed the marine fauna. Hence there is little chance of finding in Loch Lomond any living representatives of its pre-glacial fauna or flora.

Sir Herbert Maxwell and Mr. Henry Lamond kindly tell me that the char, a characteristic Alpine and northern fish, which requires cold water, is reported in the Statistical Account of Scotland, 1796, to have lived then in Loch Lomond. Mr. Lamond considers this statement probably a mistake, though, as the char has died out elsewhere, it might have disappeared in the interval. Sir Herbert Maxwell (Scottish Naturalist, 1926, p. 175), has recorded the fact that the Char disappeared from Loch Leven owing to a change of temperature due to drainage, the last Char being caught there in 1837; and he remarks that the char must have inhabited Loch Lomond at one time. The powan or white-fish (*Coregonus clupeoides*) is a cold water survival, which is now found in Scotland only in Loch Lomond and Loch Eck.

## IV. The Structure of the Loch Lomond Basin.

The evidence for an anticlinal axis in the Loch Lomond Series is confirmed by the Geological Survey map, sheet 38, as the prevalent dip of the foliation in the schists for three miles N. from Luss is usually between 50° and 70° to S. or S.S.E. Proceeding northward the dips are gentler, but still to the S; dips of 10° to 30°; are common in the lower and middle parts of Glen Douglas. In the upper part of that glen and thence to Tarbet the dips are northward and usually from 15° to 30°, with a few up to 40°. Then follows a belt of undulating dips, which are often horizontal or gently N. or S., until further N., beyond the albite-gneiss belt, the dip is steeply and irregularly northward. The same arrangement holds on the eastern side of Loch Lomond. The dips are southward, S. of Inversnaid and of the schistose-quartzite ridge of Meall Mor; the dips are marked on the Geological Survey map as northward on the northern side of Meall Mor, and southward on its southern side; the northerly dip continues thence to the edge of sheet 38 and into sheet 46.

The dips are less regular W. of the loch, and N. of Tarbet, there is a considerable area where the strike is N. and S. and the dips are westward.

Sir Archibald Geikie is fully justified in his claim that the High-

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land Boundary Fault has had no share in the formation of Loch Lomond; for that fault was formed in Devonian times, and crosses the loch obliquely. It does not even support Sir Archibald Geikie's view that valleys along faults are merely due to denudation; for that fault outcrops along the crest of Conic Hill and crosses the loch at its shallow part.

A sheaf of faults, which are parallel to the loch, occurs beside its fiord part. Over 20 of the faults are marked on the Survey Map and there are others. A fault W. of Ben Dubh (2108 ft.), crosses the head of Ben Striddle (tributary to the Luss Water) and continues northward W. of Rudha Mor and is in line with the fault on the eastern side of the loch behind "the rocks of Craig Royston," so well known from Scott's "Macgregors' Lament."

A conspicuous fault of this series at Sput Ban may be seen from the steamer, N. of Rowardennan; this fault cuts through biotite-gneiss and schist which is contorted by the fault, and beside it are many veins and eyes of quartz; the fault passes below the waterfall and trends north-westward and later returns to its northern course. The cliff made by this fault can be seen from the loch rising up the hill, N. of the waterfall. A fault, with a downthrow to the W., passes quarter of a mile W. of the summit of Ben Lomond, and another, a mile to the S., forms the western front of Sron Aonaich.

Others are marked on the Geological Survey map N. of Inversnaid, along the Snaid Burn, and through Maol an Fhithid and Stob nan Eighrach; another E. of Ardlui, reaches the shore of the loch at Ardleish, and its southward extension appears to determine the straight eastern shore of the loch nearly as far S. as Rob Roy's Cave, N. of Inversnaid. On the western side of the loch further faults with a trend from N. by E. pass behind Rudha Ban and Ardvoirlich to Inveruglas, and continue further S. through Arrochar and to the E. of Loch Long; and an important fault, W. of Rudha Mor, is in line with the N. to S. dyke behind Rowchois on the eastern side.

These faults are subsidiary to the main fault of Loch Lomond which is probably along the line of greatest depth. The deepest part, as remarked by Mr. Henry Lamond, is nearer the eastern than the western shore; and the rise from it is steeper eastward than westward.

Along most of the loch the eastern side is the straighter and steeper. The western side is more broken and falls more gradually

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to the shore. The loch basin is of the asymmetric type, and is due to subsidence along a N. to S. fault near the eastern side of the loch; the strip of country to the W. of the fault has foundered and been tilted. The strike of the rocks on the western side is in many places N. and S., which practically never occurs on the eastern side. Thus between Kenmore (S. of Inveruglas) and Tarbet, the Survey map records 16 dips with a N. to S. strike. They are due to tilting along a meridional axis between a pair of faults, whereas the strike on the opposite side of the loch keeps its normal trend to E.N.E. (Fig. 33). The original displacement of

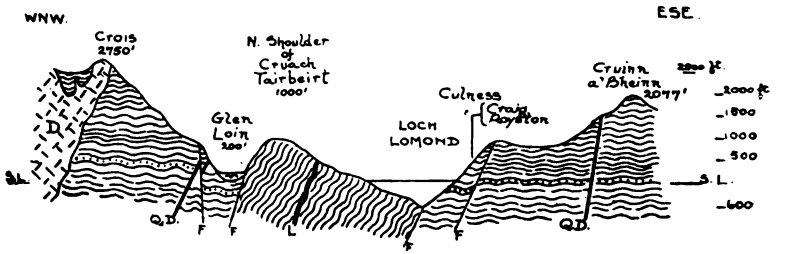


Fig. 33.

~~ Alluvium of Glen Loin. D.—Diorite of Ben Arthur. Q.D.—Quartz-Dolerite Dykes. L.—Lamprophyre Dykes. F.—Faults. S.L.—Sea Level.

this block is doubtless Devonian; but the difference between the opposite sides of the loch indicate a Pliocene movement by a downthrow along the fault under Loch Lomond. The existence of a fault along Loch Lomond is shown by the outcrops on the western side being thrown to the S. This fault must be Devonian, but its existence led to fresh movements and the opening of a great tension cleft during the Pliocene uplift. The frequent minor earthquakes at the foot of the Ochills and at Comrie are attributed to slips along the Ochil and Highland Boundary faults; and the earthquake which drove the people out of church at Drymen and caused the wave on Loch Lomond (Phil. Trans. Vol. 49, 1756, p. 389) on the 1st of November, 1755, the morning of the Lisbon earthquake, indicate that slight movements still happen along the Loch Lomond Fault.[1]

[1] This earthquake wave is one of the most famous phenomena in the geology of Loch Lomond. It has been often attributed to a direct consequence of the Lisbon earthquake with which it was almost simultaneous. The disturbance began on Loch Lomond at 9.30 a.m., lasting to 10.15; the Lisbon earthquake is dated as 9.40; Lisbon time is 16 minutes later than that of Loch

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That the Tarbet-Arrochar gap lies along faults is indicated by the dykes; the two dykes along the southern side of the gap are probably along strike faults. A parallel series of cross faults runs from behind Rudha Ban, near the northern end of Loch Lomond, down Glen Loin and Loch Long, and one of them forms the Glen Culanach and continues to the head of the Gareloch. This set of faults is connected with the formation of Loch Long and the Gareloch.

The ages of these faults is not adequately known for they are not in contact with any post-Paleozoic rock. They are obviously of different dates, as some of them cut the Devonian lamprophyres but not the Permian quartz-dolerites. The faults belong to at least four series—pre-Paleozoic; Middle Devonian; Upper Carboniferous-Permian; and Pliocene. In Cowal the Kainozoic dykes are dislocated by faults connected with the fiord valley system; some of the faults of Loch Lomond are doubtless also later than the Kainozoic dykes, and are therefore Pliocene or perhaps late Miocene.

## V. The Origin of the Loch Lomond Basin.

Loch Lomond lies in a long trough cutting across the sedimentary rocks which strike to E.N.E., and as the predominant trend of the loch is to 10° W. of N., it crosses the strike of the rocks at an angle of about 80°. The origin of the basin is traditionally ascribed to glacial erosion. As the loch basin is an obvious continuation of Glen Falloch there seems no reason from the relief of the country why either water or ice should have cut out a valley 600 ft. below sea level along that course unless guided by some pre-existing plane of weakness. If the Loch Lomond basin be regarded as due to ice descending from the Ben Lui group, that movement would not explain Glen Falloch.

The Loch Lomond Valley is obviously of no great geological

Lomond. The agitations of the water along the southern coast of England varied from about 10.35 at Portsmouth, 11 at Reading, after 11 in the Thames at Rotherhithe, noon at Yarmouth; the Scilly Isles and western Cornwall at 2 p.m., Swansea 6-7 p.m. The shock felt in the lead mines in Derbyshire was at 11 a.m.; the wave in Loch Ness was before 10 a.m. Hence it appears that the cause which produced the Lisbon earthquake produced almost simultaneous but independent movements on the Loch Lomond and Loch Ness faults, the waves there being an hour earlier than the accurately timed disturbances at Portsmouth and elsewhere in the south of England.

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antiquity, for its upper part has a steep eastern wall, and has the characters of a relatively young valley. The older valleys of the district, as was pointed out by H. M. Cadell (1886, p. 346; and Gregory, 1915, p. 296, pl. 31) cross the site of the loch from W.N.W. to E.S.E. Thus the hanging valley of Dubh Eas from the western side is continued through a wind-gap to Glen Gyle and Loch Katrine. The valley of Loch Sloy continued across Loch Lomond to Loch Arklet. The river from Glen Luss, with that from Glen Douglas as a northern tributary, doubtless passed through the Drymen-Blane-Campsie valley to the Kelvin. The Loch Lomond trough is subsequent to this old river system, and has diverted the drainage through the Leven to the lower Clyde.

The case for the glacial origin of Loch Lomond has been stated, amongst others, by Sir Archibald Geikie (1901, pp. 254-61) who points out that the loch crosses the Highland Boundary Fault, which, at the most, has only occasioned a slight deepening of the basin along its course. Sir Archibald Geikie remarked (1901, pp. 254, 256), that the evidence is not sufficiently complete to justify a dogmatic verdict and that the basins were determined by pre-existing depressions.

There is no apparent reason from the relief of the country why a powerful river or glacier should have passed along the line of Loch Lomond, unless some plane of weakness had enabled the river to excavate a valley, and the ice subsequently to occupy and enlarge it.

The tectonic origin of the Loch Lomond Basin was advocated by Kinahan in 1875. He held that the basin was due to fractures, and that the deepest parts were due to the intersection of cross fractures. The fractured rock was removed by ice which he said " accomplished the major portion of the excavation along broken lines of rock due to faults and other shrinkage fissures." (Kinahan, 1875, p. 214). The action of the ice he represented as dependent on the fractures, for in the basin " if due to the erosion of ice, the deeps and shallows ought to graduate into the others, and have a trend conformable with the lie of the valley, and consequently with the course of the glacier; this, however, is contrary to facts ! " He recognised moreover that some of the deeps were due to subsidences, such as that N. of Hunter's Bank, N. of the Douglas delta (*Ibid.*, p. 213), and he considered some of the dislocations to be post-glacial (*Ibid.*, p. 216). He also recognised that the shallowness of the loch at the southern end was not due

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to silting as it has in places a rock bottom, and that at one time the loch was a fiord connected with the sea (*Ibid.*, p. 210).

Kinahan's explanation seems to me on the right lines, and the faults and dislocations required by it are now fully established.[1] The loch basin is a member of the fiord valley system of western Scotland, the arguments for the tectonic origin of which need not be here repeated. (*Cf.* " Nature and Origin of Fiords," 1913; for Loch Lomond, see pp. 178, 438, &c.). As there remarked the loch owes its existence primarily to one main fault. The existence of the islets, and especially those in the northern part, are obstacles to the glacier erosion theory and the obliquity of the valley both to the strike of the rocks and the older river drainage supports its tectonic origin. The basin is one of those asymmetrical fiord valleys due to subsidence along one main fault, like the Sound of Jura, where the fault is along the straight steep western shore, while the eastern side is irregularly indented owing to the drowning of the valleys. The main Loch Lomond fault lies under the loch but nearer the eastern shore which rises as a steep scarp, while the western side is less regular owing to the sinking of the valleys and the tilting of the sunken block. As Mr. H. Lamond has remarked to me, the deepest line is along the eastern side, with a steeper eastern than western uprise, as shown especially by the 500 ft. contour. The shore line on the western side of Loch Lomond is more angular than is usual in this type of valley, as the block from Tarbert northward has been tilted between two secondary faults, which have altered the strike of the rocks from the normal trend of E.N.E. to a trend N. and S.

The Loch Lomond basin may therefore be regarded as a tectonic depression due to the Pliocene uplift of Scotland, during which tension clefts fractured the country and the floor of the loch sank along a main N. and S. fault attended by numerous parallel and secondary faults. These faults cut across the country regardless alike of the strike of the rocks and the course of the pre-existing

[1] This view is emphatically opposed to that of R. L. Jack (1877, p. 6), and James Geikie (1894, p. 827, pl. XVI), who has given a figure by Jack showing the depth of Loch Lomond to true scale which he claims to show that its slopes are imperceptible. The diagram is on too small a scale to show the steeper slopes which Kinahan had in mind. James Geikie's statement (1894, p. 229), that " no fault or dislocation of the solid strata is known to cross the area occupied by the Loch " is contradicted by the Geological Survey Map, and the faults referred to previously. Any pre-glacial dislocations on the floor of the loch would have been rounded by the ice.

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valleys. The subsidence left the eastern wall as a fault scarp now softened and worn back by weathering, while the western side is less regular owing to its faulted tilted sunken strip; but the main western valleys, having sunk, have gentler gradients than those of the streams which fall from the hanging valleys on the eastern side.

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## No. XIII.—The Classification of Scottish Carboniferous Olivine-Basalts and Mugearites. By A. G. MacGregor, M.C., B.Sc.

(Read 8th March, 1928; issued 22nd September, 1928).

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### I.—Introduction.

From the days of Hutton onwards, the Carboniferous basalts of Scotland have been made the subject of geological researches which have gradually become more and more detailed. This is

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the natural result of three chief causes; the close proximity of the main volcanic areas to three centres of Scottish geological thought in Edinburgh, Glasgow and St. Andrews; the intimate association of the volcanic products with the coals, ironstones, and other deposits of economic value which have been intensively wrought in the Midland Valley of Scotland; and the rapid development of petrographic technique since the microscope was first applied to the study of rocks.

Thus increasing numbers of workers from Scottish Universities and Geological Societies have naturally turned their attention to the elucidation of Carboniferous vulcanicity, while the members of the Geological Survey and their collaborators have been confronted by the same problems during the original mapping and subsequent revision of the Scottish Coalfields. The application of the microscope to the study of the rocks enabled the enthusiastic followers of the pioneers to establish a number of 'types' which were found to be of common occurrence in different localities; and so a detailed classification arose.

At first this classification was used purely for descriptive purposes, but of late years Survey workers in particular, engaged in mapping large areas of Carboniferous basaltic lavas, have distinguished on their maps the outcrops of different types, and in this way much has been learned of the structure of the lava fields and of the history of the vulcanicity.

It is proposed to consider here the names at present used to describe the various olivine-bearing basaltic lava types, with particular reference to the changes which have been made since the historical accounts of Sir John S. Flett (1910, chapter XV.)[1] and Dr. G. W. Tyrrell (1913, pp. 221-232). A critical discussion is needed at the present time because various writers have modified or extended the original definitions of some of the types, and a certain amount of ambiguity has in consequence arisen.

The opportunity will be taken to present a table of all analyses published up to date, and what is believed to be a complete set of references to the literature of research on the olivine-basalt types and mugearites from 1892 to the present day.[2]

[1] Dates refer to Bibliography, pp. 356-359.

[2] Many references to all types of Carboniferous basalt and to mugearites will be found in the forthcoming Revised Geological Survey Memoirs:—'Explanation of Sheet 22 (Kilmarnock),' and 'Explanation of Sheet 23 (Hamilton)'; 'The Geology of Arran' (in the press) should also be consulted.

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## II.—General Discussion of the Classification.

### (*a*)—The Two Main Groups:—Macroporphyritic and Microporphyritic Olivine-basalts.

On the more recent 1 inch to the mile colour-printed maps published (or about to be published) by the Geological Survey[1] a primary division of the basalt lavas has been made into two broad groups, macroporphyritic and microporphyritic basalts, which are distinguished by different shades of red.[2] These fundamental subdivisions were expressed in part in Flett's classification of 1910 (1910, p. 316), but in the third edition of the 1 inch map of the Edinburgh District (Sheet 32, published 1910), as on previously published geological maps of the Midland Valley of Scotland, all the Carboniferous basalt lavas were shown by the same colour. It was in 1911 that the Survey classification was modified in detail by Bailey, who divided the Carboniferous basalt lavas of the Campsie Fells, Kilpatrick Hills and Carmunnock Hills (Cathkin Braes) into two main groups, macroporphyritic and microporphyritic (1911, pp. 135-140; and 1925, pp. 175-180). In consequence, on the Glasgow District map of 1911, to which attention has already been drawn, a colour distinction between these two main groups was first made, and the structural features of the basalt lavas thus clearly brought out.

Bailey, in describing the macroporphyritic and microporphyritic groups of basalt lavas of the area dealt with in the Glasgow District Memoir, did not lay down definite limits of size for the discrimination between 'macro-phenocrysts' and 'micro-phenocrysts.' This unfortunately led Tyrrell, in his paper on the Kilpatrick Hills (1913, pp. 233-34), to define microporphyritic Carboniferous basalts as those in which phenocrysts are visible in thin section only, and macroporphyritic Carboniferous basalts as those in which the phenocrysts are conspicuous and identifiable in hand specimens. This definition by Tyrrell does not conform to the meaning which Bailey intended to convey by the term 'microporphyritic.' Crystals which Survey workers call 'micro-

[1] Map of the Glasgow District, 1911; Sheet 31, Airdrie, 1924; Sheet 22, Kilmarnock, 1928, Sheet 23, Hamilton (in the press).

[2] We are not concerned in this paper with the trachyandesitic, trachytic and rhyolitic lavas which are distinguished by an orange colour, but we shall include the *mugearites*, which are closely allied to one of the basalt types, and are represented by a third colour, yellowish-buff.

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phenocrysts ' are relatively small compared with the phenocrysts of the macroporphyritic basalts, but are usually easily seen and identified in hand specimens.

Accordingly, in order to avoid confusion, I give here approximate numerical values to the current terms ' macroporphyritic' and ' microporphyritic ' as applied to Scottish Carboniferous basalts by the Geological Survey.

In typical *macroporphyritic* basalts certain minerals occur as large phenocrysts, which are numerous and conspicuous to the naked eye. Many of these phenocrysts exceed 2 mm. across their maximum diameter, 3 mm. to 4mm. being a common measurement, which may however be exceeded.

In typical *microporphyritic* basalts the phenocrysts are also numerous, but less conspicuous owing to their smaller size; they can still be seen easily with a pocket-lens, and in many cases with the naked eye. The phenocrysts rarely attain a maximum diameter of 2 mm., an order of magnitude of about 0.5 mm. to 1.0 mm. being common.

Basalts are also found which are intermediate between the two types defined above, the size of the phenocrysts being of the order of 2 mm. across. Such types have been mapped and coloured along with the macroporphyritic or microporphyritic groups *according to their local associates*. On the latest Survey 1 inch maps, however,[1] the occurrence and nature of these passage-types are indicated by appropriate *lettering*[2] on the face of the map at the actual outcrops.

The presence of these intermediate types has not been found in practice to prevent the solution of the main structural problems of the lava-fields. Elucidation of structure in the large lava areas *can only be rendered possible* by dividing the very abundant and widespread basalt lavas into groups to be separated on the map by different colours.[3] In spite of its arbitrary simplicity the method of grouping adopted has been justified by results.[4] As

[1] *e.g.*, 1 inch Sheet 22 (Kilmarnock), and 1 inch Sheet 23 (Hamilton) in the press.

[2] See p. 350.

[3] The more acid rocks mentioned above as differentiated by colour from the basalts are often absent or very meagrely represented in large areas, and so give little assistance.

[4] A summary of the results achieved in the Clyde Lava Plateau has recently been given to the Society by Mr. J. E. Richey (1928a).



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a matter of fact any more elaborate subdivision for mapping purposes is impracticable in the case of the Geological Survey, since the scheme must be applicable to very large areas, in many parts of which scarcity of exposures and complexity of structure makes ultra-detailed mapping impossible.

Fortunately, in spite of Tyrrell's definition of 'macroporphyritic' and 'microporphyritic' the great majority of rocks classified according to the tabular scheme given in his paper on the Kilpatrick Hills would conform to Survey usage as regards macro- and micro-phenocrysts. The only difficulty would be with rocks where phenocrysts average about 2 mm. or a little less. These would almost certainly go into Tyrrell's macroporphyritic division: but no great harm is done if a transitional rock has in the past been classified as belonging to one or other of the types which it approaches. This has frequently been done by Survey petrographers.

(*b*).—Subdivisions of the Main Groups.

For descriptive purposes the macroporphyritic and microporphyritic groups have been subdivided into various types in accordance with the very sensible system initiated by Hatch and Watts (1897, p. 417-18). Instead of introducing different '—ite' names for closely allied varieties of basalt (which—locally at least—it is desirable to distinguish), the locality of the type specimen of each variety is used to qualify the broader term 'basalt' *e.g.*, 'basalt of Dalmeny type' or, more shortly, 'Dalmeny basalt.'

A tabular representation of the classification as at present adopted by Survey workers on Scottish Carboniferous petrology, will be found on page 360a. The history of the evolution of this scheme is fully discussed from p. 330 onwards where further details of the microscopic characters of each type will be found under the appropriate heading. It should by now be clearly understood that the division into macroporphyritic and microporphyritic groups was introduced purely to enable the field-geologist to map out different bands without constant reference to the microscope. The two primary groupings of our classification, then, are based arbitrarily on an easily distinguished field-character, the presence or absence of conspicuous phenocrysts. The subdivisions within each group are however essentially

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mineralogical, being based on the presence or absence of *certain* minerals as phenocrysts. It will be seen from the detailed descriptions and table of analyses (p. 352), that within each of the main groups (macroporphyritic and microporphyritic), there is a variation in chemical composition largely dependent on the proportion of total felspar to ferromagnesian minerals; and certain mineralogical and chemical similarities may be found between a member of the one group and a member of the other. These points will be briefly discussed later. In the meantime we would stress the fact that macro- and micro-porphyritic grouping has no obvious petrogenetic significance: it does not for instance separate the basalts into groups with distinct chemical characteristics, or fundamental mineralogical differences.

It cannot be too strongly emphasised that the Scottish Carboniferous basalts form a *continuous rock-series*. Although the types selected in the classification represent the mode of consolidation of the great bulk of the rocks, we may find in all districts various passage types, some intermediate between certain members of the macroporphyritic and microporphyritic groups respectively, others intermediate between certain macroporphyritic types and still others which mark a passage from one microporphyritic type to another (see p. 349).

(*c*)—Main Trend of Departures from the Earlier Classifications.

The detailed classification of Hatch and Watts (1897, p. 418), on which the modern nomenclature is based, was devised when only a relatively limited number of Carboniferous rocks had been examined under the microscope. It is a proof of the soundness of their work that their scheme is applicable in a recognisable form to the many hundreds of slices which have been cut since that time. They would however have required superhuman foresight to enable their classification to stand unchanged until to-day.

The cause of the main changes in the classification is to be found in the extension, within reasonable limits, of the mineralogical and textural variations admitted within each type, so as to include under the same name widely developed suites of basalts with many characters in common.

The experience gained by Survey workers during the study of the large number of slices of Scottish Carboniferous basalts, which have been made since the time of the detailed classifications of Watts (1897, p. 418) and Flett (1910, p. 316), has shown that it is undesirable to base a distinction between different types or

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groups of porphyritic olivine-basalt or dolerite on the presence of ophitic or sub-ophitic relations between the augite and felspar of the groundmass, as opposed to idiomorphic or granular habit of the augite in the groundmass.

Thus in 1911 Bailey re-defined the term ' Jedburgh basalt ' to include rocks, in which the groundmass (in conformity with the original description) was sub-ophitic or micro-ophitic, and others in which it was microlitic—*i.e.*, with idiomorphic or granular augite (1911, pp. 138-9). Again in the same publication (1911, p. 137), he referred to Watts' ' Kilsyth type of dolerite ' as merely a rather unusual variety of Markle basalt. Watts had separated the two types because in the Kilsyth rock the groundmass was micro-ophitic, while in the Markle type it was microlitic.

Both Watts and Flett in their classifications referred to porphyritic Carboniferous olivine-bearing lavas and intrusions with a sub-ophitic or micro-ophitic groundmass as ' dolerites,' as opposed to the ' basalts ' in which the groundmass augite was idiomorphic or granular. In accordance with the recommendations of the Committee on British petrographic nomenclature (1921a, pp. 138-9), this criterion for discriminating between a dolerite and a basalt is no longer used by the Geological Survey. The distinction now depends on coarseness of texture alone, and no definite limit can be laid down between the two types. The term ' dolerite ' is used for a coarse-grained rock of basaltic composition, which may be of hypabyssal or of volcanic origin. ' Basalts ' as compared with ' dolerites ' are more compact and fine-grained, and in hand specimens appear rather aphanitic to the naked eye. Basalts, like dolerites, may be intrusive or extrusive.

## III.—Detailed History of Classification and Research.

### (*a*)—Macroporphyritic Group.

(i) *Markle Type.* (Plate XI, Fig. 1). The type Markle basalt (from Markle Quarry lava flow, East Lothian) was first described by Hatch as a ' labradorite basalt ' (1892, p. 119). The term ' basalt of Markle type ' was first defined by Flett (1910, p. 316) as a rock with numerous large phenocrysts of plagioclase, and small and inconspicuous olivines in a fine *non-ophitic* groundmass which may be partly glassy. Bailey, in his description of the Markle basalt lavas of East Lothian (1910b, pp. 120-21), pointed out that the felspar phenocrysts are labradorite in the

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type rock, and that the groundmass (which consists of felspar, augite, olivine, and magnetite) is more felspathic than in the Dunsapie and Craiglockhart types, and that in addition to labradorite laths it contains a considerable quantity of alkali-felspar (oligoclase and orthoclase). A little later Bailey described Markle basalts (lavas and intrusions) in his *macroporphyritic* basalt group of the Campsie and Kilpatrick Hills (1911, pp. 110, 136; and 1925, pp. 147, 177), where orthoclase is distinctly less abundant in the groundmass than in the type rock. Bailey suggested also that Watts' 'Kilsyth type of dolerite,' adopted unchanged by Flett (1910, p. 317), and differing from the previously defined Markle basalt in the sub-ophitic character of the groundmass augite, should be dropped, and that rocks which agree with Watts' definition of the Kilsyth type ("Strongly porphyritic olivine-dolerite; felspar phenocrysts large; olivine smaller; groundmass sub-ophitic" (1897, p. 418), should be classed as merely unusual varieties of Markle basalt.

This view has been adopted by the Survey, and virtually by Tyrrell in his detailed description of the petrology of the Calciferous Sandstone volcanic rocks of the Kilpatrick Hills, where lavas and intrusions of Markle type are found (1913, pp. 229, 234, 241-4). Tyrrell however retained the Kilsyth type *as a sub-variety of the Markle type*, characterised by ophitic groundmass. This appears to the writer as carrying subdivision too far, in view of the limited distribution of the rocks.[1]

Markle basalts may now be defined as members of the macroporphyritic group of basalts which carry numerous phenocrysts (many or all of which are of macroporphyritic dimensions) of plagioclase (about labradorite to bytownite in composition), usually accompanied by a few porphyritic olivines (not generally macro-phenocrysts), in a groundmass of felspar (laths approximating to labradorite and usually accompanied by oligoclase or

[1] Mr. J. Phemister, who has recently re-surveyed the neighbourhood of Carnwath (1 inch Sheet 23), finds there a persistent but thin development of a type of basalt which agrees very closely with the slice from Berryhill Farm, north of Kilsyth, quoted by Bailey in the Glasgow memoir as that on which Watts based his Kilsyth type. The rocks differ from the normal Markle basalts in the beautifully ophitic relations between the augite and felspar of the groundmass, and in the increased amount of augite. Rocks like that of Berryhill farm are therefore more widespread than was previously suspected, but, in order that our classification may be consistent they are to be classed as an ophitic, rather basic variety of the Markle type.

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orthoclase—in some cases in considerable amounts) with augite, iron-ore, and usually olivine. The augite of the groundmass (yellowish, fawn-brown, or purplish) is generally idiomorphic or granular, but its relation to the felspar may be sub-ophitic or ophitic. The groundmass is often, but not necessarily, more felspathic than in the Dunsapie type. A common accessory is apatite, while chlorite and other viriditic material often occupies interspaces, and scraps of biotite and brown hornblende (both of late formation) are sometimes found.

Basalts of Markle type and of Calciferous Sandstone age have been recorded and described from various parts of Southern Scotland. Some occurrences have already been cited. In addition, lavas have been described by Lothian from the Kilsyth Hills (1902, pp. 16-22); an intrusion by Lady McRobert from Melrose (1914, p. 312); lavas and dykes by Harrison from the East Kilsyth Hills (1916, pp. 317-18, 321); lavas, dykes and sills by Smellie from Bute (1916a, pp. 339, 344, 347-8, 349-50, 355); lavas, dykes, sills and plugs by Tyrrell from the Cumbraes (1917, pp. 246-51, 260-61); sills and dykes by Leitch and Scott from West Renfrewshire (1917a, pp. 276-8, 282); lavas by Lady McRobert from the Border Country (1920a, pp. 90, 92); lavas by Peach and Flett from Arthur's Seat (1921, especially appendix, pp. 25-6);[1] lavas and dykes by McCallien from Kintyre (1927, pp. 70, 88, 91-5); lavas by Dinham from the Gargunnock Hills (1927b, p. 473).

(ii) *Dunsapie type.* (Plate XI, Fig. 2). The Dunsapie type of basalt (type locality Dunsapie intrusion, Edinburgh) was defined by Flett in 1910 (1910, pp. 316-7), as an olivine-basalt with abundant large conspicuous phenocrysts of olivine augite and plagioclase felspar in a non-ophitic rather coarse groundmass, sometimes with glass and usually with analcite and biotite. In the same publication Flett separated the 'Lion's Haunch type' of basalt although very similar to the Dunsapie type. In the following year Bailey re-defined the Dunsapie type (1910b, p. 119), so as to include and replace the terms 'Lion's Haunch type' and 'Kippie Law type' (1897, p. 418),[2] and in his description of the Glasgow District, also in 1911 (1911, p. 136; and 1925, p.

[1] The First Edition (1911), by Peach, contains no petrological appendix.

[2] Watts' type slice from Kippie Law did not represent the average rock of the exposure from which it came. The Kippie Law lava is a Dunsapie basalt: Watts' Kippie Law type is not.

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176), the Dunsapie type was included in his macroporphyritic group. Tyrrell in 1913, in his account of the lavas and intrusions of the Kilpatrick Hills, adopted Bailey's Glasgow District definition, but retained the Lion's Haunch type as a sub-type of Dunsapie basalt with glass in the groundmass (1913, pp. 230, 234).

Following Bailey, the term 'Dunsapie type' has replaced 'Lion's Haunch type' in Survey publications.[1] Although the Lion's Haunch rock is indexed as 'Dunsapie type' on the map which accompanies each edition of the 'Description of Arthur's Seat Volcano,' various references in the texts are made to the 'Lion's Haunch type' of basalt, and Flett, in the petrographical appendix attached to the second edition, gives a brief description of the 'Lion's Haunch basalts.' This is a useful addition to the memoir, for, as he points out, the rock has been figured in geological and petrographical treatises and is consequently well-known to students in all parts of the world (1921, p. 25). The basalt of the Lion's Haunch is a macroporphyritic vent-intrusion with certain characters which give it an individuality of its own. Rocks which reproduce all its peculiarities are however of very restricted occurrence in the Scottish Carboniferous. In essentials the Lion's Haunch basalt is like the Dunsapie type as defined by Bailey in the Glasgow Memoir. Bailey's definition covers a group of Carboniferous basalts which are both abundant and very widespread in Scotland, and so the restricted and comparatively isolated Lion's Haunch basalt is no longer used as a type-rock in mapping lavas or intrusions.

Basalts of Dunsapie type may now be defined as members of the macroporphyritic group of basalts, which carry numerous phenocrysts (many or all of which are of macroporphyritic dimensions) of plagioclase (from about labradorite to bytownite in composition), augite (yellowish, fawn-brown, or purplish), and olivine, in a groundmass of plagioclase (near labradorite in composition but a little less basic felspar, often near oligoclase, may be present), augite, iron-ore and usually olivine. A little chlorite or other viriditic material, chlorophaeite, analcite, or glass may be present in interspaces, and accessories may include apatite, and scraps

[1] See for instance the map of Arthur's Seat Volcano which is bound with the Edinburgh District Memoir quoted above, and the 'Description of Arthur's Seat Volcano' (*Mem. Geol. Surv. Scotland*), 1911, p. 16 and Map, and Second Edition, 1921, p. 16 and Map. The only map on which the 'Lion's Haunch type' appears in the index is the Edinburgh sheet (1910a).

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of biotite and brown hornblende (both of late formation). The augite of the groundmass (yellowish, fawn-brown, or purplish), is almost always idiomorphic or granular, but sub-ophitic or or ophitic relations between augite and felspar would not exclude a rock from the type. The proportion of felspar and ferromagnesian minerals in the groundmass may vary somewhat but felspar is always abundant.

Basalts of Dunsapie type and Calciferous Sandstone age, in addition to the occurrences already mentioned, have been recorded and described from both the East and West of Scotland. Lavas and dykes have been described by Harrison from the East Kilsyth Hills (1916, pp. 320, 322), lavas by Smellie from Bute (1916a, pp. 344, 356); dykes, sills and plugs by Tyrrell from the Cumbraes (1917, pp. 246-51, 260-63); lavas and plugs by Lady McRobert from the Border Country (1920a, p. 91); intrusions by Allan from Fife (1924, p. 48; 1926, p. 3); lavas and dykes by McCallien from Kintyre (1927, pp. 70, 89, 93, 98). Chlorophaeite was recorded as a common vesicle-mineral in the basalt of the Lion's Haunch, Arthur's Seat, by Campbell and Lunn in 1925 (1925a, p. 440).

(iii) *Craiglockhart type.* (Plate XI, Fig. 3). The type locality of the Craiglockhart basalt is the lava of Craiglockhart Hill, Edinburgh. The rock was described by Sir A. Geikie, and later by Hatch, but the first use and definition of the term ' basalt of Craiglockhart type ' was by Watts (1897, p. 418). Flett, following Watts, included the Craiglockhart type in his conspicuously porphyritic basalts with large phenocrysts of augite and olivine and with *non-ophitic* groundmass (1910, pp. 316, 318). Bailey used the term Craiglockhart type in describing lavas and intrusions of Calciferous Sandstone age in East Lothian (1910b, p. 118). In the following year in describing lavas and intrusions of the same age in the Campsie and Kilpatrick Hills, he put basalts of Craiglockhart type in his macroporphyritic group, and, extending Flett's *definition*, included rocks in which the augite of the groundmass was *sub-ophitic* (1911, p. 136; and 1925, p. 176). Tyrrell, in his description of the lavas and intrusions of Craiglockhart type in the Kilpatrick Hills, used the term for basalts with macroporphyritic crystals of augite and olivine, but did not mention the relations of augite and felspar in the groundmass (1913, pp. 231, 234, 246-8).

Basalts of Craiglockhart type may now be defined as members

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of the macroporphyritic basalt group which carry numerous phenocrysts (many or all of which are of macroporphyritic dimensions) of augite (yellowish, fawn-brown, or purplish) and olivine, in a groundmass of augite (yellowish, fawn-brown or purplish), iron-ore, felspar (near labradorite in composition), and usually olivine. The proportion of ferromagnesians (especially iron-ore) to felspar tends to be greater than in the Dunsapie type. The augite of the groundmass may be granular or idiomorphic or its relations to the felspar may be sub-ophitic or ophitic. Apatite is a frequent accessory and small amounts of interstitial chlorite or other viriditic material may be present. A rock otherwise like a Craiglockhart basalt but with other accessories such as those found in Markle and Dunsapie types, would still be classed with the Craiglockhart group.

References to Craiglockhart basalts of Calciferous Sandstone age, besides those already mentioned, will be found chiefly in the *Transactions* of the Geological Society of Glasgow. A lava has been described by Lothian from the Kilsyth Hills (1902, p. 18); lavas have been described by Harrison from the East Kilsyth Hills (1916, pp. 317, 324); lavas and intrusions by Smellie from Bute (1916a, pp. 344, 349, 356); lavas by Peach and Flett from Arthur's Seat (1921, especially Appendix, p. 25);[1] lavas by McCallien from Kintyre (1927, pp. 70, 97-98).

(iv) *Field Characters of Macroporphyritic basalts.*

In the field the macroporphyritic basalts, when fresh, are dark-grey to black rocks in which plagioclase is transparent, augite black, and olivine sometimes glassy and yellow. Normally however, the rocks are weathered and rusty, and olivine is frequently conspicuous because it is represented by dark-red irony pseudomorphs (' iddingsite '). Olivine may also be pseudomorphed by green serpentine and by white calcite. In a weathered outcrop felspar is cloudy or may even be replaced by white calcite, and augite may be partly or completely pseudomorphed by pale cloudy carbonate. It is therefore necessary to examine very carefully white or dirty-white phenocrysts in the decomposed macroporphyritic basalts.

Another difficulty is produced by albitization (1909, pp. 250-256; 1913, p. 243; and 1916a, pp. 361-362), a phenomenon not uncommon in Markle basalts in particular. The effect is often to give the rock a very pale grey colour, and it may then be con-

[1] The First Edition (1911), by Peach, contains no petrological appendix.

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fused with some porphyritic trachybasalts, trachyandesites, and trachytes. Only field experience can get over this trouble.

(*b*)—Microporphyritic Group.

(i) *Jedburgh type.* (Plate XII, Fig. 2). The Jedburgh type of ' olivine-dolerite ' was defined by Watts, its founder, as follows: ' porphyritic elements inconspicuous, olivine being the principal and felspar of secondary inportance; groundmass sub-ophitic ' (1897, p. 418). Flett in 1910 adopted Watts' definition, and classed lavas of the Jedburgh type from Arthur's Seat, Edinburgh, among his porphyritic olivine-dolerites with a sub-ophitic or micro-ophitic groundmass (1910, pp. 316, 321).[1]

Unfortunately Watts gave no definite type locality and it is therefore impossible to fit his description to any particular Survey slice from the Jedburgh Area (1 inch Sheet 17).[2] Most of the slices however belong to a natural petrographical group which is also abundantly represented in the lavas and intrusions of the Western part of the Campsie Fells of the Glasgow district. Accordingly Bailey, in his description of the latter area, made use of the term ' Jedburgh type ' for one of the sub-divisions of his group of microporphyritic *olivine-basalts.* He *re-defined the term,* however, so as to include closely allied rocks found both in the Jedburgh and Campsie districts (1911, pp. 138-40; and 1925, pp. 178-80).

Tyrrell, when describing the lavas and intrusions of Jedburgh basalt from the Kilpatrick Hills in 1913 (1913, pp. 226-27, and 232-38), accepted Bailey's re-definition of the type in the Glasgow Memoir, but suggested certain extensions which will be referred to below.

At this point it is convenient to present the definition of Jedburgh basalt adopted in this paper. It is based on the description given in the Glasgow Memoir, but omits references to mineral combinations or structures which are to be found only in rocks transitional from true Jedburgh basalt to other types.[3] The definition has the approval of Mr. Bailey.

[1] Lavas of Jedburgh type are not shown on the small map of Arthur's Seat which is bound with the Edinburgh Memoir, nor are they mentioned in later accounts of the hill (see 1911b and 1921 in bibliography).

[2] These Survey slices represent nine bosses and one lava, all of Lower Carboniferous age, which occur within about twelve miles of Jedburgh.

[3] For characters of transitional types see p. 350.

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A Jedburgh basalt is a member of the microporphyritic olivine-basalt group which typically has numerous roughly parallel lathy micro-phenocrysts of plagioclase felspar (near labradorite in composition) together with usually rather less numerous microphenocrysts of olivine, in a groundmass of felspar (near labradorite in composition but a little less basic felspar may be present), augite and iron-ores. The rock *as a whole* is dominantly felspathic. Although flow-structure, as shown by parallelism of microporphyritic felspars, is the typical habit, the Jedburgh type may be extended to cover microporphyritic olivine-basalts more felspathic than those of the Dalmeny type, but with felspars showing very poorly developed microporphyritic character and with or without good flow structure. Augite (yellowish, fawn-brown, or purplish), is always restricted to the groundmass where its relation to the felspar may be micro-ophitic or sub-ophitic, or on the other hand idiomorphic or granular (microlitic groundmass). Various accessories such as glass or analcite may be present but apatite, chlorite and other viriditic materials are commonest.

Tyrrell suggested that the Jedburgh type might be extended to include rocks which conform to Bailey's definition but for the fact that they carry microphenocrysts of augite in addition to those of felspar and olivine (1913, p. 227). Such rocks would perhaps be better described as *transitional* types; they might be passage types either to Dalmeny basalts or to Dunsapie basalts according to the number of augite phenocrysts and the general characters of the rocks. A discussion of Tyrrell's suggestion that the " Gallaston type of basalt " should be regarded as a variety of Jedburgh basalt will be found on p. 340.

Bailey's re-defined Jedburgh basalts occupy a position intermediate between Dalmeny basalts and mugearites. The greater importance of total felspar relative to ferromagnesian minerals as compared with the Dalmeny type is seen at once on comparing the analyses given in the table on p. 352.

The analysis of the Jedburgh type (by E. G. Radley) is quoted from the Glasgow Memoir (1925, p. 182). The analysed rock, which occurs as a small intrusion in Little Caldon neck, north of the Kilpatrick Hills, is a good example of a Jedburgh basalt with micro-ophitic groundmass. In it the typical parallelism of felspar micro-phenocrysts is also well seen. Tyrrell has

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determined the Specific Gravity of the Little Caldon Jedburgh basalt (1909b, p. 340).

Two examples representative of Bailey's re-defined Jedburgh type may be quoted from the Jedburgh District (1 inch sheet 17).

(1) Dunian Hill, 2 miles south-west of Jedburgh. An intrusive plug or boss. Jedburgh basalt with sub-ophitic to micro-ophitic groundmass (1946).[1]

(2) Neides Law, 12 miles south of Jedburgh. An intrusive plug or boss. Jedburgh basalt with ' microlitic ' groundmass—*i.e.*, augite idiomorphic as little prisms and grains (1943).[1]

*Field Characters.* In the field Jedburgh basalts are grey to dark-grey rocks when fresh. They often have a very thin pale-weathering crust, and close-set platy jointing is a characteristic feature. (A similar structure is shown even more strikingly in the mugearites). Microporphyritic character is generally more obscure than in the Dalmeny type, and to the naked eye the rocks appear compact and non-porphyritic. If the rock has ' trachytic ' structure—as is generally the case—the numerous parallel felspar micro-phenocrysts may be seen with a pocket-lens, or when bright light is reflected to the naked eye from a smooth broken surface. Olivines may often be seen without recourse to the microscope. In an area of Scottish Carboniferous basalts it is fairly safe to map as a Jedburgh basalt any grey apparently non-porphyritic fine-grained rock, *unless it weathers to a rather pale colour all through.* In the latter case the rock is more probably a mugearite or trachybasalt. Passage types, between Jedburgh basalts and mugearites in character, are not uncommon and cannot be distinguished in the field.

Besides occurrences already referred to, Jedburgh basalts of Lower Carboniferous age have been described as follows: intrusions by Tyrrell from the Auchineden district (1909b, pp. 338-40); lavas and intrusions by Harrison from the East Kilsyth Hills (1916, pp. 327-32); lavas by Smellie from Bute (1916a, pp. 355-56); lavas and intrusions by Tyrrell from the Cumbraes (1917, pp. 244-73); intrusions by Leitch and Scott from West Renfrewshire (1917a, pp. 276-77, 283-84); lavas and plugs by Lady McRobert from the Border Country (1920a, pp. 91-94); lavas, dykes and sills by McCallien from Kintyre (1927, pp. 70,

[1] These numbers refer to slices in the Scottish collection of the Geological Survey.

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87, 89, 95-97); lavas by Dinham from the Gargunnock Hills (1927b, p. 473).

(ii) *Dalmeny type.* Plate XII, Fig. 3). The rock on which the Dalmeny type of basalt was based was first described by Hatch in 1892 (1892a, p. 130). The type locality is a quarry in a small lava-flow of Calciferous Sandstone age, near Dalmeny Church, West Lothian. The first definite use of the term ' basalt of Dalmeny type ' was by Watts in 1897 (1897, p. 418); he defined the type as follows: " Porphyritic olivine abundant, augite much less common, and felspar rare or absent; groundmass with granular or idiomorphic augite (one of the most common types)." Watts included the Dalmeny type in his group of olivine-basalts, as opposed to his olivine-dolerite group in which the groundmass is sub-ophitic.

The above definition was adopted by Flett (1910, pp. 316, 319), Bailey (1911, p. 138), and Tyrrell (1913, p. 233), with little modification. Flett defined the phenocrysts as ' small and inconspicuous,' and mentioned in his description that in *some* examples in the Edinburgh district, the augite is *in part* micro-ophitic to ophitic. He defined the type however, as being essentially non-ophitic. Bailey, followed by Tyrrell, classed Dalmeny basalts as micro-porphyritic and with microlitic augite.

In 1925, however, Bailey, as has been briefly mentioned above, definitely extended the Dalmeny type to include " coarser varieties in which the augite of the groundmass occurs as sub-ophitic granules " (1925, p. 178). He pointed out that such rocks are very characteristic of the Millstone Grit volcanic horizon in Ayrshire, and suggested that they could alternatively be described as fine-grained basalts, or dolerites, of Galliston type.

It is now proposed to omit the ' Galliston type ' from the classification scheme of Scottish Carboniferous basalts. In this connection we may consider the following facts:

(1) The type locality is Galliston quarry, near Kirkcaldy, Fifeshire. The name of the type quarry has been misspelt as ' Gallaston ' by numerous writers including Hatch and Watts, the originators of the type (1892a, p. 130; and 1897, p. 418). This leads to confusion.

(2) The rock of the type locality (an intrusion), is so coarse-grained that its texture makes it a dolerite and not a basalt. It is a special variety of a sill of variable texture.[1]

[1] Allan states that the Raith dolerite suite of intrusions, to which the rock of

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(3) Rocks which closely resemble the type ' Gallaston dolerite ' (of Galliston quarry) are unknown or of very limited occurrence in the Lothians, Lanarkshire, Renfrewshire, and Ayrshire, and (as far as my information goes) in Fifeshire.

(4) The lavas to which Flett has referred in the Edinburgh Memoir as belonging to the " Gallaston type of dolerite " (1910, p. 321), although they are somewhat coarser in grain than the average Dalmeny basalt described before that date, are otherwise very like them except for the more or less sub-ophitic structure of the matrix. They are decidedly finer in grain than the type rock of Galliston quarry, and much less markedly sub-ophitic. They very closely resemble the lavas of the Millstone Grit volcanic horizon in Ayrshire (1 inch Sheet 22).

(5) The Millstone Grit lavas of Ayrshire are a widespread set of rocks which are singularly uniform in type, and almost identical with Flett's ' Gallaston dolerites ' of the Edinburgh district. Some examples are sub-ophitic but others are not. Few or none are so coarse as to fall outside the limits of microporphyritic olivine-basalts as defined above—a definition based on the general Survey use of the term since its inception.

(6) The analysis of a typical Millstone Grit lava proves to be practically identical with that of the type Dalmeny basalt (see analysis table p. 352).

(7) Examination of a sliced specimen from the Dalmeny quarry (recently collected for analysis) reveals the fact that *the groundmass of the type Dalmeny basalt is in part sub-ophitic.*

(8) Tyrrell has re-defined the ' Gallaston type of basalt ' as an olivine-rich variety of ophitic Jedburgh basalt (1913, pp. 227, 233), on the assumption, presumably, that an ophitic rock cannot be classed with the Dalmeny type. This seems an unfortunate re-definition as, apart from the ophitic structure, Tyrrell's ' Gallaston ' basalts of the Kilpatrick Hills are, from his description, much more closely related to Dalmeny basalts than to Jedburgh basalts *as re-defined by Bailey in* 1911 (see p. 336). Moreover the structure and texture of typical ophitic Jedburgh basalts known to me are unlike either those of the type rock of Galliston quarry, or of Flett's ' Gallaston dolerites ' from the Edinburgh district.

Galliston quarry belongs, is very variable in composition, texture and structure. He evidently could not apply the term ' Galliston type ' to the suite as a whole, (1924, p. 495).

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(9) The rock of Galliston quarry has been analysed (1924, p. 497), and on turning to the analysis table (p. 353) it will be seen that it agrees more closely in composition with the Hillhouse than with the Dalmeny type. To avoid confusion then we must distinguish between Flett's 'Gallaston Dolerites' of the Edinburgh district and the type rock of Galliston quarry, for the former closely resemble analysed rocks with the composition of Dalmeny basalts (i.e. the Millstone Grit basalt lavas), while the latter has a composition very near that of the Hillhouse type.

In view of this formidable array of contradictions it seems best to discard the term 'Gallaston' (or more correctly 'Galliston') type to extend the term Dalmeny type to include basalts with a sub-ophitic or ophitic groundmass, and so to class the Millstone Grit lavas of Ayrshire as Dalmeny basalts. These Millstone Grit basalts as a group have certain characteristic features of their own which are outlined below. In general mineralogical and chemical composition however, they so closely resemble the Calciferous Sandstone examples that they are not worthy of constituting a separate type.

The rock of Galliston Quarry should not in future be used as a *type*. It is a coarse sub-ophitic olivine-dolerite which forms one part of a sill of variable structure and texture, and it is not a type to which a known suite of Scottish Carboniferous basalts or dolerites approximates in structure, texture and composition. If future work should show that rocks like that of Galliston quarry have a considerable distribution in Scotland, a new type locality could be chosen.

The term Dalmeny basalt is therefore now defined as a rock containing numerous micro-phenocrysts of olivine—which may be accompanied by a few micro-phenocrysts of augite (yellowish, fawn-brown, or purplish), and sporadic microphenocrysts of plagioclase felspar (near labradorite in composition), in a groundmass of felspar (near labradorite in composition but a little less basic felspar may be present) with abundant augite and iron-ore. The groundmass augite (yellowish, fawn-brown, or purplish) may be idiomorphic or granular (microlitic groundmass) or its relation to the felspar may be sub-ophitic or ophitic. Flow structure produced by parallelism of felspars may be seen but is not common. The rocks may be fine-or coarse-grained, the coarsest examples being in the border-line between porphyritic olivine basalts and olivine-dolerites. Various accessories may

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be present in small amount—*e.g.*, apatite, chlorite or other viriditic material, chlorophaeite, glass, analcite.

Typical Dalmeny basalts of the Millstone Grit horizon[1] do not differ essentially from some of the coarser-grained examples of Dalmeny basalt of Calciferous Sandstone age. Sub-ophitic relations between augite and felspar are however much more common; the dimensions of the olivine micro-phenocrysts and of the felspar laths are greater on the average; and good flow structure is never found. The augite tends to be aggregated together in many small or large groups, and rod-like iron-ores are of frequent occurrence. Patches of isotropic interstitial matter of bright orange-red or of green colour are very often present. Combinations of some or all of the above characters give to many Millstone Grit lavas a distinctive appearance in thin section.

*Field Characters.* In the field, Dalmeny basalts, when fresh, are dark-grey or black, and the microporphyritic olivines sometimes glassy yellow. The rocks however, are usually somewhat weathered and stained with rust, and the olivines show up very conspicuously, as they are often completely pseudomorphed by dark red 'iddingsite.' Dalmeny basalts have not got the close-set platy joints of the Jedburgh type, nor do they weather with a pale crust.

Some augite and sporadic felspar microphenocrysts may be present. Some examples (*e.g. some* of the Millstone Grit Dalmeny basalts) may be coarse and verge on doleritic rocks with phenocrysts approaching 2 mm.

Besides the references already given, descriptions of Dalmeny basalts or of Galliston Dolerites will be found in the papers of the following authors, as enumerated. Lavas and intrusions have been described by Geikie from Fife (1900, pp. 53, 67, 81-2); lavas (mainly) by Falconer from the Bathgate Hills (1905, pp. 359-66, and 1906, pp. 133-37);[2] lavas by Campbell and Stenhouse from Inchcolm (1910d, p. 122); lavas and intrusions by Tyrrell from the Kilpatrick Hills (1913, p. 240); a dyke by Harrison from the East Kilsyth Hills (1916, pp. 325, 333); plugs by Lady

[1] For petrographical and field descriptions see the forthcoming (Revised) Geological Survey Memoir which describes 1 inch Sheet 22 (Kilmarnock) and also G. V. Wilson 'The Ayrshire Bauxitic Clay,' (*Mem. Geol. Surv. Scotland*), 1922, especially pp. 13-15.

[2] To find how Falconer's classification corresponds to Survey nomenclature see the Edinburgh District Memoir (1910, p. 317).

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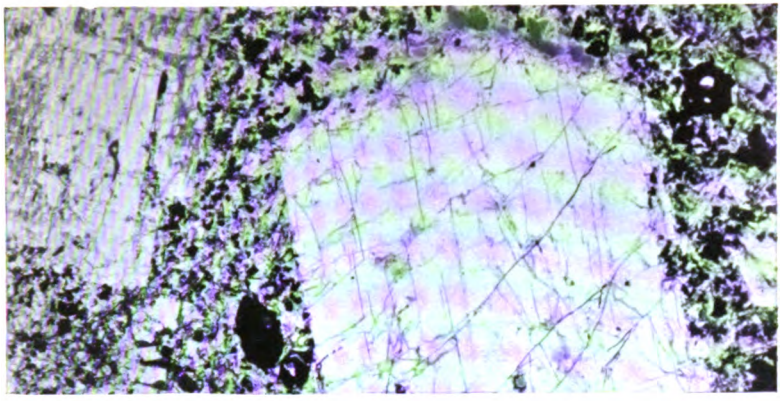

Fig. 1.—MARKLE TYPE.

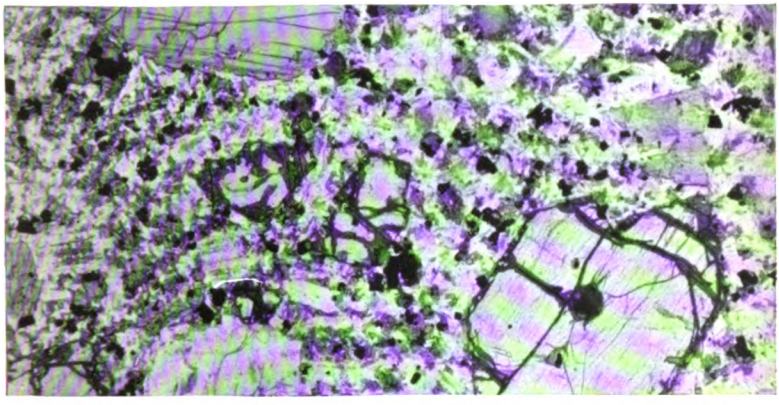

FIG. 2.—DUNSAPIE TYPE.

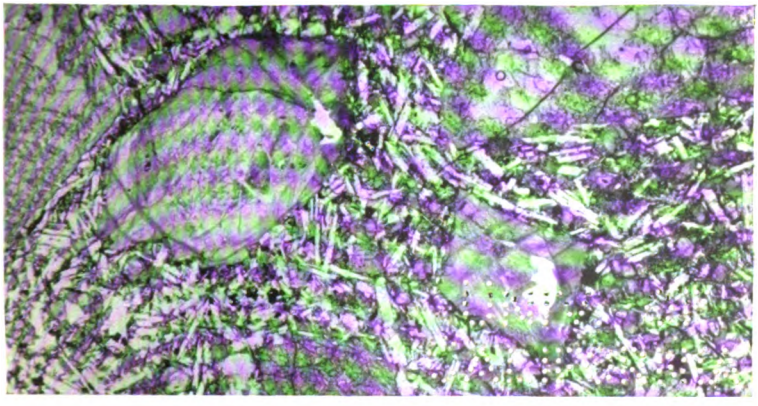

FIG. 3.—CRAIGLOCKHART TYPE.

*Photo. F. Rhodes.*

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McRobert from the Border Country (1920a, pp. 92-94); an intrusion by Peach and Flett from Arthur's Seat (1921, especially appendix p. 26);[2] lavas by Walker from Dalmeny (1923, pp. 362, 366, 374); lavas and intrusions by Allan from Fifeshire (1924, especially pp. 484, 489, 495; and 1926, pp. 3, 10); lavas by by McCallien from Kintyre (1927, pp. 98-9).

(iii) *Hillhouse type.* (Plate XII, Fig. 4). The type locality for Hillhouse basalt is Hillhouse Quarry, located in a sill of the Bathgate Hills. Flett was the first to apply to the rock the name " basalt of Hillhouse type ' (1910, pp. 316, 320), but it had originally been studied by Hatch (1892a, p. 129), and later classified by Watts (1897, p. 418), as ' basalt of Picrite type.' Flett defined the type as having a non-ophitic groundmass full of augite with little felspar, and sometimes partly glassy, and carrying many small and inconspicuous phenocrysts of olivine and a few of augite. This definition was essentially the same as that of Watts' ' Picrite type,' which however made no mention of glass in the groundmass. The term ' basalt of Hillhouse type ' replaced that of ' basalt of Picrite type ' and Flett pointed out (1910, p. 317) that Falconer's ' type No. 4 ' of the lavas of the Bathgate Hills (1906, p. 136) was identical. In this connection it may be noted that Falconer in his description of ' type No. 4 ' made no statement as to the relative numbers of olivine and augite phenocrysts.

Bailey stressed the point that the Hillhouse type closely approaches the limburgites, and may have analcite in the groundmass. (Flett had recorded analcite but had not included it in his definition of the type). Bailey placed the Hillhouse basalt in his microporphyritic olivine-basalt group (1911, p. 138; and 1925, p. 178). Tyrrell, in 1913, made no further changes in the classification (1913, pp. 228, 233).

Carboniferous basalt lavas closely allied to the Hillhouse type have recently been described from the Burntisland district, Fifeshire by Allan (1924, p. 484), under a new title—' Basalt of Kinghorn Type.' The Kinghorn type departs essentially from the previously defined Hillhouse type in the following respect only: the microphenocrysts of augite and olivine occur in nearly equal proportions.

The following facts have been found by examination of (1) the microscope slide cut from the analysed specimen from Hillhouse quarry (1911, p. 142; and 1925, p. 182); (2) two microscope slides,

[1] The First Edition (1911), by Peach, contains no petrological appendix.



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cut from another specimen collected in Hillhouse Quarry, part of one of which (the type slide) is illustrated in the Memoir on the Edinburgh District (1910, Plate XII, Fig. 6).

(1) The analysed rock corresponds closely to Flett's *definition* of the Edinburgh Memoir (1910, p. 316), for in it phenocrysts of olivine are decidedly more numerous than those of augite.

(2) In the other slides mentioned above, porphyritic augite crystals are, on the whole, slightly *more* abundant than the porphyritic olivines. The latter are mostly of larger dimensions than the augites, as in the Kinghorn type (1924, p. 484). The slices correspond to the description on page 320 of the Edinburgh Memoir, but not *strictly* to the definition (based on Hatch's picrite type) on page 316 of the same work.

We find then that in different hand specimens from the same quarry—the type locality—the relative numbers of olivine and augite microphenocrysts vary considerably, and that the augites may even exceed the olivines in number.

The definition on page 316 of the Edinburgh Memoir, if rigidly followed, is therefore not general enough to apply to the rock of the type quarry as a whole. It seems better to re-define the Hillhouse type, so as to include all variations found in the type quarry, and thus also to include Allan's ' Kinghorn type.'

A further justification of this procedure will be found in the close correspondence between the analyses of the type rock of Hillhouse quarry and the type Kinghorn basalt of Chuck Hall quarry (see analysis table). In the case of the Jedburgh, Dalmeny, and Hillhouse types the analyses are quite distinctive. Again, the classification initiated by Hatch and Watts, and modified by Flett and Bailey, is such that in the field the geologist can allocate many olivine-basalt outcrops to one or other type with fair certainty by the aid of a pocket-lens. To discriminate in this way between a Hillhouse basalt (as defined by Flett) and a Kinghorn basalt would, I think, be impossible.

The Kinghorn type, then, does not appear suitable for incorporation in a classification to be adopted by Geological Survey workers. (*cf.* p. 328). If, in very detailed work on a suitable well-exposed area, it appears advantageous to separate basalts corresponding to the Kinghorn type, the latter name could be used as a variety of the Hillhouse type as re-defined here.

The Hillhouse type of basalt may now be defined as a member of

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the microporphyritic basalt group, in which the porphyritic constituents are olivine and usually augite. Olivine phenocrysts are always abundant; porphyritic augites may be practically absent, less numerous than, or rather more numerous than the olivines. The groundmass contains iron-ore, very abundant augite, *and relatively little felspar* (labradorite or rather more basic plagioclase) together with a variable amount of glassy base, or analcite. The colour of all the augite is usually decidedly purple, and ophitic or sub-ophitic structure is rarely, if ever, found.

*Field description* In the field Hillhouse basalts basalts resemble Dalmeny basalts but are darker in colour when fresh and usually finer in grain. They are perhaps most frequently found as neck-intrusions.

In addition to those already given, the papers of the following authors give other references to Scottish basalts of Hillhouse type. Lavas and intrusions have been described by Geikie from Fife (1900, pp. 54, 57, 80, 82)[1]; neck intrusions by Wilson from Ayrshire (1916b, p. 97); the margin of the Hillhouse sill by Day (1920, p. 50); plugs by Lady McRobert from the Border Country (1920a, pp. 92-3); lavas and intrusions by Allan from Fifeshire (1924, pp. 484, 489; and 1926, pp. 3, 10).

(c) Mugearite.

(Plate XII, Fig. 1). The type 'mugearite' was founded by Harker in 1904, to describe one component of certain composite sills of Tertiary age occurring in the Island of Skye (1904, pp. 261-69). Points mentioned are:—Phenocrysts are absent: felspar is oligoclase with subordinate orthoclase: augite is quite subordinate to olivine (or its equivalent the 'brown mineral'), and iron-ore: the little felspar laths (about .005 in.), have a trachytic arrangement: olivine is usually about 1/100 in. in diameter: augite is colourless and ophitic: magnetite occurs as octahedra and fluor-apatite as slender needles: the place of olivine may be wholly or partly taken by a unknown brown mineral: in basic varieties magnetite is of next importance to the felspar, olivine is fairly abundant and augite occurs as very small interstitial granules—not in any abundance.

The first recognition of the presence in Central Scotland of rocks of the Hebridean mugearite type was due to Barrow: he was familiar with Harker's Eigg mugearites and had recorded the

[1] In Geikie's Memoir on Central and Western Fife and Kinross, the old name 'Picrite type' is used.

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occurrence of rocks of similar type among the Carboniferous volcanic suite of East Lothian, under the provisional name of 'Congleton Rock,' as early as 1902 (1903, p. 124). The resemblance to the Eigg mugearites was, however, only stated in conversation with his colleagues on the Geological Survey.

In 1908 Harker described other Tertiary mugearites from Rum, Canna, Eigg and Muck (1908, pp. 126-34). The rocks in question in Canna, Eigg, and Muck were regarded by him as sills, but in Rum the evidence was not sufficient for him to decide whether he was dealing with surface flows or with sills. He considered the latter alternative the more probable. In some of these rocks small sparse felspar phenocrysts are present (from .01 to $\frac{1}{8}$ in.) and varying from labradorite to oligoclase in composition: a few untwinned crystals may be potash felspar: augite and magnetite sometimes form glomeroporphyritic aggregates with the felspar: magnetite is next in importance to the felspar while augite in very minute granules is less abundant but more so than in the Skye mugearites: interstitial glass or chlorophaeite may be present.

Flett was the first to determine the precise nature of the 'unknown brown mineral' of the mugearites. This material was in part a peculiar biotite and in part a peculiar hornblende (1908a, pp. 119-26). The occurrence of little flakes of biotite and hornblende has been found to be a characteristic feature of many Carboniferous mugearites.

Shortly afterwards Flett and Bailey wrote accounts of the petrology of the Carboniferous mugearite lavas of the Midlothian (1910, pp. 322-23), of the East Lothian (1910b, pp. 123-24) and of the Glasgow Districts (1911, pp. 140-43; and 1925, pp. 180-83). Some of the East Lothian rocks are described as markedly porphyritic, with large and abundant felspar phenocrysts (*e.g.*, andesine). A rock carrying two generations of olivine was also included in the mugearites. Thus the term mugearite was extended to *markedly* porphyritic rocks with *large* porphyritic felspars or olivines, in a groundmass conforming to the description of the Skye mugearites except for the non-ophitic habit of the augite. (Both these porphyritic types were however exceptional). This procedure had the approval of Harker.

Bailey's description of the mugearites of the Glasgow District seems to involve a further slight departure from a definition based rigidly on the mugearites of Skye and the Small Isles. In the Glasgow District mugearites, augite, "although markedly less

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abundant than in the basalts, is probably, on the whole, the most persistent ferromagnesian element."

Tyrrell, in his paper on the Kilpatrick Hills, classed mugearites as essentially oligoclase basalts allied chemically to the essexite family (1913, pp. 226, 233).

In the Second Edition of the Glasgow Memoir, Bailey raised the question of the upper limit of silica percentage in mugearites (1925, p. 182, footnote). He pointed out that a Mull rock with 55.76 per cent. of Silica had been classed as a mugearite by Thomas and himself although all other analysed mugearites have less than 55 per cent of silica. He suggested that it might eventually prove convenient to exclude such more acid rocks from the mugearites, but left the question open. The petrological significance of silica percentage in rock nomenclature is too wide a question to be discussed here. For the views of Thomas and Bailey the Mull Memoir may be consulted (1924b, pp. 280-81).

A comprehensive definition of mugearite may now be attempted. Mugearites are compact fine-grained rocks in which the most abundant mineral constituent is acid plagioclase largely approximating in composition to oligoclase. Subordinate orthoclase may sometimes be recognised. The felspar occurs as closely packed narrow laths whose approximate parallelism gives good fluxional (' trachytic ') structure. The length of felspar laths may range from about 0.15 mm., to 0.50 mm. (in coarser types). Other constituents are olivine, iron-ore, and augite, and the relative proportions of these minerals are very variable. Frequently olivine is more abundant than iron-ore and there is a very meagre amount of augite. Sometimes however, olivine may be quite absent, its place usually being largely taken by iron-ore. Augite in some cases is the most important ferromagnesian but it is never so abundant as in a basalt of similar grain (i.e. a similar rock with labradorite in place of oligoclase). The olivine occurs as small crystals whose length is of the same order as that of the felspar laths. The iron-ore (magnetite or titaniferous magnetite) may build tiny crystals or irregular little granules. The colourless or yellowish augite may be ophitic, or, in the form of minute shapeless granules, it may partially fill interspaces between felspar laths. Characteristic accessories are apatite and late-formed biotite and brown hornblende in the form of tiny flakes. Interstitial glass or chlorophaeite or chlorite may be found. Spherulitic quartz is sometimes seen in late veins and vesicles.

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Porphyritic mugearites are recognised, but they are not so common as the non-porphyritic varieties. The phenocrysts may include felspar varying from labradorite to oligoclase, or even potash-felspar, augite, magnetite and olivine. Phenocrysts have only rarely been described as exceeding about 2 mm. in diameter, and porphyritic olivine is most unusual.

By an increase in the lime-content of the felspars accompanied by a greater proportion of ferromagnesian minerals, especially augite and iron-ore, mugearites pass by gradual transitions into fine-grained basalts. With increase in alkalinity and restriction of the ferromagnesian constituents they grade into trachytic rocks.

One word of warning is needed:—*Rocks similar to mugearites in many respects are produced by the more or less complete albitisation of some fine-textured basalts* (1924b, p. 143; and 1927b, p. 473).

*Field description.* As regards field characters mugearites are typically very fine-grained rocks which are dark-grey when fresh. Carboniferous examples are almost always considerably weathered and the colour is altered *throughout* to pale-greyish, brownish-buff, greenish, or reddish. The flow-structure of the tiny felspar laths may be seen with a pocket-lens or when light is reflected to the naked eye from a smooth broken surface. A characteristic feature which the mugearites share with the Jedburgh basalts is the presence of close-set parallel somewhat irregular platy joints. Sometimes, however, a flow may consist almost entirely of fine spongy slag with drawn-out vesicles. In the field it is not always possible to distinguish mugearites from some exceptionally pale-weathering Jedburgh basalts on the one hand, and from some of the fresher trachyandesites and trachytes on the other. A typical mugearite however, is finer in grain than typical examples of the other rocks mentioned.

Thomas described mugearites (of pre-Upper Llandovery and possibly Lower Arenig age) from Pembrokeshire in 1911 (1911c, pp. 201-3). They compare quite well with Harker's original mugearites in both mineral constituents and chemical composition. The occurrence is interesting because it serves to emphasise the wide distribution of the type in Britain, both in space and time.

Mugearite lavas of Calciferous Sandstone age have been described by Martin and Tyrrell from the Gargunnock Hills (1908b, pp. 247-54); by Tyrrell from the Kilpatrick Hills (1913, pp. 238-40), and by Harrison from the East Kilsyth Hills (1916, pp. 325, 331).

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The same author also mentioned an andesitic mugearite dyke (1916, p. 326). Mugearite lavas of Calciferous Sandstone age have also been described by Smellie and Tyrrell respectively from the islands of Bute (1916a, p. 354), and the Cumbraes (1917, pp. 264-65) in the Firth of Clyde. Lavas have been described from Arthur's Seat by Peach and Flett (1921, especially appendix, p. 26).[1] Thomas and Bailey have recently described Tertiary mugearite lavas from Mull (1924b, pp. 143-45).

Campbell and Lunn have recently suggested that certain Carboniferous mugearites are the volcanic equivalents of hypabyssal tholeiites (1927c, pp. 499-501, 504).

In connection with the wide distribution of mugearitic rocks it is interesting to note that Washington has described from Hawaii, under the name 'olivine-oligoclase andesite,' lavas which are stated to resemble Scottish mugearites both chemically and modally (1923a, pp. 479-482).

Wells has recently suggested that the term 'mugearite' should be replaced by "oligoclase-basalt of the Mugeary type" (1924c, pp. 325-27). His paper is a contribution to the reform of the present irrational petrographic nomenclature. In the opinion of many petrologists, changes along the lines he suggests would produce excellent results, especially as regards the naming of new rock types. In the particular instance under discussion we come up against the difficulty of finding universally acceptable definitions of the terms 'basalt' and 'andesite.' This is by no means an insuperable difficulty; it could be solved by the International Geological Congress, and its solution would be of the greatest assistance to students of petrology. At present mugearite is considered by many petrologists to be a variety of 'trachybasalt' (1925, p. 182; and 1928, map index).

## IV.—The Transitional Basaltic Types.

The following notes, which may be looked on as of the nature of an appendix to the table on p. 360a, indicate briefly the main combinations of characters which are found in known rock varieties intermediate between the various standard types.

(*a*). Rocks intermediate between the macroporphyritic basalt types.

These varieties arise owing to different combinations of the

[1] The First Edition (1911), by Peach, contains no petrological appendix.

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phenocrysts present, and their nature is obvious—for instance a rock with abundant macrophenocrysts of olivine and augite, but very few of felspar, is naturally intermediate between the Dunsapie and Craiglockhart types. A rock with abundant macroporphyritic felspar phenocrysts accompanied by *abundant* olivine phenocrysts would be called an 'olivine-rich basalt of Markle type.'

(*b*). Rocks intermediate between the microporphyritic basalt types.

(i) *Rocks intermediate between the Jedburgh and Dalmeny types*, (vwB and vwD).[1] These may be microporphyritic olivine-basalts with or without flow arrangement of felspars, and with or without ophitic structure, which are not *dominantly* felspathic, but rather richer in felspar than the Dalmeny type. Microphenocrysts of felspar and sporadic microphenocrysts of augite may be present.

(ii) *Rocks intermediate between the Dalmeny and Hillhouse types*, (vuB and vuD). These are microporphyritic olivine-basalts which are richer in augite (and to a less extent in olivine) at the expense of felspar, than the Dalmeny basalts.

(*c*). Rocks intermediate between macroporphyritic and microporphyritic basalt types.

(i) *Rocks intermediate between the Jedburgh and Markle types*, (wzB and wzD). These rocks have a groundmass like a Jedburgh basalt but contain sporadic macroporphyritic felspar phenocrysts; *or* contain abundant felspar phenocrysts which average only about 2 mm.

(ii) *Rocks intermediate between the Jedburgh and Dunsapie types*, (wyB and wyD). These rocks with a groundmass approximating to that found in different varieties of Jebdurgh basalt, which carry a number of augite microphenocrysts in addition to the felspars and olivines, *or* which have abundant phenocrysts of felspar, augite and olivine averaging only about 2 mm.

(iii) *Rocks intermediate between the Dalmeny and Markle types*, (vzB and vzD). These rocks may carry microporphyritic olivines together with a good many microporphyritic felspars; *or*, the porphyritic elements (olivines with many felspars) average only about 2 mm. The groundmass is as in Dalmeny or Markle types.

[1] For explanation of letters see table on p. 360a.

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(iv) *Rocks intermediate between the Dalmeny and Dunsapie types*, (vyB and vyD). These rocks may carry abundant microporphyritic olivines together with a good many microporphyritic augites and felspars; *or*, the porphyritic elements (abundant olivines, augites, and felspars) average only about 2 mm. The groundmass is as in Dalmeny or Dunsapie types.

(v) *Rocks intermediate between the Dalmeny and Craiglockhart types* (vxB and vxD). These rocks may carry abundant microporphyritic olivines *and augites*; *or*, the porphyritic elements (abundant olivines and augites) average only about 2 mm. The groundmass is as in Dalmeny or Craiglockhart types.

(vi) *Rocks intermediate between the Hillhouse and Craiglockhart types* (uxB and uxD). These rocks have abundant phenocrysts of augite and olivine which average only about 2 mm., set in a groundmass like that found in the Hillhouse type, *i.e.*, with very little felspar.

(*d*). Rocks intermediate between Markle basalts and mugearites.

These rocks have phenocrysts of plagioclase and some of olivine in a felspathic groundmass in which the felspar laths largely approximate to oligoclase-andesine or andesine, perhaps accompanied by some orthoclase. Sporadic augite phenocrysts may also be present.

(*e*). Rocks intermediate between Jedburgh basalts and mugearites.

By a decrease in the proportion of ferromagnesian minerals, especially augite and iron-ore, and a reduction of the lime-content of the felspars, accompanied by decrease in size and loss of the microporphyritic character of the latter, Jedburgh basalts pass by gradual transitions into mugearites.

## V.—Brief Discussion of Analyses.[1]

No attempt will be made here to give an exhaustive discussion of the chemical composition of the basaltic lavas, but a few notes on the table of analyses are necessary.

[1] Norms of certain of these analysed olivine-basalts and mugearites have been published: seee Tyrrell (1913, p. 250), Harrison (1916, p. 324), Smellie (1916a, p. 359); also H. S. Washington. 'Chemical Analyses of Igneous Rocks.' United States Geol. Survey, Prof. Paper No. 99, 1917, pp. 497, 613, 649. For variation diagrams see Bailey (1910b, p. 122) and Tyrrell (1913, p. 252).

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ANALYSES OF SCOTTISH CARBONIFEROUS

| | I | II | III | IV | V | VI* | VII | VIII | IX | X |
|---|---|---|---|---|---|---|---|---|---|---|
| TYPE | Markle | Markle | Markle | Dunsapie | Dunsapie | 'Dun-sapie' | Craig-Lockhart | Jedburgh | Dalmeny | Dalmeny |
| $SiO_2$ | 49.54 | 49.07 | 45.62 | 46.01 | 45.10 | 49.76 | 46.28 | 46.45 | 46.24 | 46.16 |
| $TiO_2$ | — | — | 2.09 | — | 2.66 | 2.01 | 2.06 | 3.11 | 2.54 | 2.36 |
| $Al_2O_3$ | 22.23 | 19.43 | 18.17 | 19.19 | 15.04 | 13.80 | 14.18 | 16.98 | 13.83 | 13.60 |
| $Cr_2O_3$ | — | — | — | — | — | — | — | — | 0.02 | 0.01 |
| $Fe_2O_3$ | 9.55 | 10.58 | 1.28 | 5.91 | 8.85 | 6.72 | 3.79 | 3.94 | 1.92 | 3.19 |
| FeO | 1.12 | 2.35 | 8.30 | 6.75 | 4.62 | 7.68 | 7.34 | 8.57 | 9.36 | 9.39 |
| MnO | 0.08 | 0.32 | 0.35 | 0.19 | 0.45 | p.n.d. | 0.09 | 0.48 | 0.15 | 0.15 |
| (Co, Ni) O | — | — | — | — | — | — | 0.05 | n.f. | — | — |
| MgO | 2.80 | 4.36 | 6.48 | 6.81 | 6.68 | 2.86 | 10.82 | 5.94 | 9.51 | 8.84 |
| CaO | 7.19 | 7.87 | 9.43 | 8.68 | 8.71 | 7.46 | 9.88 | 7.64 | 10.06 | 9.41 |
| SrO | — | — | tr. | — | 0.04 | — | n.f. | — | — | — |
| BaO | — | — | tr. | — | p.n.d. | — | n.f. | n.f. | ? 0.00 | 0.04 |
| $Na_2O$ | 4.56 | 3.31 | 4.22 | 3.27 | 3.78 | 4.70 | 2.58 | 3.50 | 2.53 | 2.81 |
| $K_2O$ | 1.81 | 0.98 | 1.43 | 1.20 | 1.04 | 1.62 | 1.01 | 1.48 | 1.71 | 1.36 |
| $Li_2O$ | — | — | — | — | — | — | ? tr. | ? tr. | ? 0.00 | ? 0.00 |
| $H_2O$ (+) | } 2.42 | } 2.26 | 1.54 | } 3.07 | 1.76 | 2.01 | 1.66 | 1.68 | 0.71 | 1.52 |
| $H_2O$ (—) | | | 0.47 | | 1.31 | 0.54 | 0.31 | 0.24 | 0.32 | 0.37 |
| $P_2O_5$ | — | — | 0.71 | — | 0.56 | 0.39 | 0.44 | 0.51 | 0.47 | 0.47 |
| $CO_2$ | — | — | none | — | none | — | n.f. | 0.41 | 0.63 | 0.12 |
| Cl | — | — | — | — | — | — | n.f. | — | — | — |
| F | — | — | — | — | — | — | — | — | — | — |
| S | — | — | — | — | — | — | n.f. | — | — | — |
| $FeS_2$ | — | — | — | — | — | — | — | tr. | 0.15 | 0.08 |
| $Fe_7S_8$ | — | — | — | — | — | — | — | 0.06 | ? 0.00 | ? 0.00 |
| | 101.30 | 100.53 | 100.09 | 101.08 | 100.60 | 99.55 | 100.49 | 100.94 | 100.15 | 99.88 |
| Sp. gr. | 2.7 | 2.76 | — | 2.8 | — | 2.81 | — | (2.895)† | — | — |

* Not a true Dunsapie (see p. 355). † not analysed specimen. n.f. = not found. p.n.d. = percentage not determined. tr. = trace. Sp. gr. = specific gravity.

I. *Olivine-basalt* (*Markle type*). Lava. Markle Quarry, East Lothian (629).[1] Anal. J. S. Grant Wilson; quoted from Hatch, *Trans. Royal Soc. Edinburgh*, vol. xxxvii, 1892, p. 119. [Not very fresh].

II. *Olivine-basalt* (*near to Markle type*). Lava. Hailes Castle, East Lothian (630). Anal. J. S. Grant Wilson; quoted from Hatch, *op. cit.*, p. 119. [Not fresh].

III. *Olivine-basalt* (*Markle type*). ? Intrusion. Road of access to Burn Crooks Waterworks, Authineden Hill, Kilpatrick Hills, Dumbartonshire. Anal. A. Scott; quoted from Tyrrell, *Trans. Geol. Soc. Glasgow*, vol. xiv, part III, 1913, p. 244. [Fresh].

[1] Numbers in brackets refer to rock-slices in the Scottish collection of H. M. Geological Survey.

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## OLIVINE-BASALTS AND MUGEARITES.

| | XI | XII | XIII | XIV | XV | XVI | XVII | XVIII | A |
|---|---|---|---|---|---|---|---|---|---|
| TYPE | Dalmeny | Hill-house | 'King-horn' | 'Gal-liston' | Mugear-ite | Mugear-ite | Mugear-ite | Mugear-ite | Mugearite |
| $Si O_2$ | 46.18 | 42.49 | 43.56 | 44.50 | 49.29 | 50.29 | 50.24 | 50.06 | 49.24 |
| $Ti O_2$ | 2.44 | 2.51 | 2.85 | 1.90 | 2.27 | 1.67 | 3.09 | 2.46 | 1.84 |
| $Al_2 O_3$ | 13.56 | 13.85 | 13.77 | 14.48 | 16.66 | 18.11 | 15.01 | 15.72 | 15.84 |
| $Cr_2 O_3$ | n.d. | — | n.d. | n.d. | — | — | — | — | tr. |
| $Fe_2 O_3$ | 1.21 | 2.59 | 2.50 | 3.13 | 7.24 | 4.09 | 8.94 | 3.94 | 6.09 |
| Fe O | 8.83 | 9.32 | 9.51 | 9.01 | 4.81 | 8.06 | 6.46 | 7.63 | 7.18 |
| Mn O | 0.16 | 0.29 | 0.24 | 0.20 | 0.55 | 0.65 | — | 0.30 | 0.29 |
| (Co Ni) O | n.d. | 0.09 | none | none | 0.04 | n.f. | — | 0.03 | tr. |
| Mg O | 10.47 | 11.21 | 10.81 | 12.26 | 2.42 | 3.32 | 3.16 | 3.82 | 3.02 |
| Ca O | 9.93 | 9.76 | 10.00 | 9.55 | 5.63 | 1.70 | 5.61 | 5.90 | 5.26 |
| Sr O | n.d. | — | n.d. | n.d. | — | n.f. | — | — | tr. |
| Ba O | n.d. | 0.04 | n.d. | n.d. | ? tr. | n.f. | — | 0.03 | 0.09 |
| $Na_2 O$ | 2.45 | 2.39 | 2.72 | 1.77 | 4.98 | 5.06 | 3.47 | 4.55 | 5.21 |
| $K_2 O$ | 0.97 | 0.87 | 0.46 | 0.79 | 1.86 | 2.65 | 1.91 | 2.16 | 2.10 |
| $Li_2 O$ | — | n.f. | — | — | tr. | ? tr. | — | n.f. | — |
| $H_2 O(+)$ | 2.40 | 3.35 | 2.45 | 1.80 | 2.11 | 3.45 | 1.77 | 1.36 | 1.61 |
| $H_2 O(-)$ | 0.44 | 0.47 | 0.77 | 0.60 | 0.34 | 0.86 | 1.05 | 0.67 | 1.08 |
| $P_2 O_5$ | 0.60 | 0.61 | 0.27 | 0.18 | 0.24 | 0.44 | — | 0.64 | 1.47 |
| $CO_2$ | none | 0.22 | none | none | 2.32 | n.f. | — | 1.08 | — |
| Cl | — | — | — | — | ? tr. | — | — | 0.04 | — |
| F | — | — | — | — | — | — | — | — | 0.18 |
| S | — | — | — | — | n.f. | — | — | — | 0.03 |
| $Fe S_2$ | — | n.f. | — | — | — | 0.06 | — | n.f. | — |
| $Fe_7 S_8$ | — | — | — | — | — | — | — | — | — |
| | 99.64 | 100.06 | 99.91 | 100.17 | 100.76 | 100.41 | 100.71<br>Less O for Cl | 100.39<br>0.01<br>100.38 | 100.53<br>Less O for F 0.07<br>100.46 |
| Sp. gr. | 2.96 | — | 2.97 | 2.98 | — | — | — | — | 2.79 |

n.d.=not determined. n.f.=not found. tr.=trace. sp. gr.=specific gravity.

IV. *Olivine-basalt* (*Dunsapie type*). Lava. Kippie Law Quarry, East Lothian (631). Anal. J. S. Grant Wilson; quoted from Hatch, *Trans. Royal. Soc. Edinburgh*, vol. xxxvii, 1892, p. 118. [*Olivine probably serpentinised*].

V. *Olivine-Basalt* (*Dunsapie type*). Plug. Duncomb Hill, Kilpatrick Hills, Dumbartonshire. Anal. A. Scott; quoted from Tyrrell, *Trans. Geol. Soc. Glasgow*, vol. xiv, part III, 1913, p. 247. [Olivine serpentinised; otherwise fresh; iron-ore abundant; augite phenocrysts sporadic].

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VI. *Olivine-basalt* (*so-called Dunsapie type*). Dyke. 1000 yards from Faughlin Reservoir, in the Faughlin Burn north tributary. Anal. J. V. Harrison; quoted from Harrison, *Trans. Geol. Soc., Glasgow*, vol. xv, part III, 1916, p. 323. [Not fresh].

VII. *Olivine-basalt* (*Craiglockhart type*). Lava. Knoll S. E. of Redside, East Lothian. (10590). Anal. E. G. Radley; quoted from 'The Geology of East Lothian.' (*Mem. Geol. Surv. Scotland*), 1910, p. 121. [Fresh].

VIII. *Olivine-basalt* (*Jedburgh type*). Plug. Little Caldon neck, N. of Kilpatrick Hills, Stirlingshire (13303). Anal. E. G. Radley; quoted from 'The Geology of the Glasgow District' (*Mem. Geol. Surv. Scotland*), 2nd Edition, 1925, p. 182. [Fresh].

IX. *Olivine-basalt* (*Dalmeny type*). Lava. Quarry 230 yards S. of Dalmeny Church, Linlithgowshire (25062a). Anal. B. E. Dixon; quoted from 'Summary of Progress for 1926' (*Mem. Geol. Surv.*), 1927, p. 77. [Fresh].

X. *Olivine-basalt* (*Dalmeny type*). Lava of Millstone Grit age. Quarry left of Annick Water, 700 feet E 35° S. of Rashillhouse, Ayrshire (25065). Anal. B. E. Dixon; quoted from 'Summary of Progress for 1926' (*Mem. Geol. Surv.*), 1927, p. 77. [Fresh].

XI. *Olivine-basalt* (*Dalmeny type*). Intrusion. High Binn, Burntisland, Fifeshire. Anal. F. Walker; quoted from Allan, *Proc. Univ. of Durham Phil. Soc.*, vol. vii 1926, p. 10. [Fresh].

XII. *Olivine-basalt* (*Hillhouse type*). Sill. Hillhouse Quarry, near Linlithgow, West Lothian (14075). Anal. E. G. Radley; quoted from 'The Geology of the Glasgow District' (*Mem. Geol. Surv. Scotland*), 1911, p. 142. [Fresh].

XIII. *Olivine-basalt* ('*Kinghorn*' *type*).[1] Lava. Chuck Hall Quarry N. of Burntisland, Fifeshire. Anal. W. H. Herdsman; quoted from Allan, *Trans. Royal Soc., Edinburgh*, vol. liii, part III, 1924, p. 497. [Fresh].

XIV. '*Galliston type of olivine-dolerite.*'[2] Sill. Galliston Quarry, Kirkcaldy, Fifeshire. Anal. W. H. Herdsman; quoted from Allan, *op. cit.*, p. 497. [Fresh].

XV. *Mugearite*. Lava. Corston Hill, Mid-Lothian (12710). Anal. W. Pollard; quoted from 'The Geology of the Neighbourhood of Edinburgh.' (*Mem. Geol. Surv. Scotland*), 1910, p. 323. [Not fresh].

XVI. *Mugearite*. Lava. 500 yards S. 30° W. of the cairn of Lairs, above Lennoxtown, Stirlingshire (13354). Anal. E. G. Radley; quoted from 'The Geology of the Glasgow District.' (*Mem. Geol. Surv. Scotland*), 1911, p. 142. [Not fresh].

XVII. *Mugearite*. Lava. Creag a' Mhara, S. Bute. Anal. J. V. Harrison; quoted from Smellie, *Trans. Geol. Soc. Glasgow*, vol. xv, part III, 1916, p. 359. [Possibly not fresh].

XVIII. *Basaltic Mugearite*. Lava. West one of two knobs (1500 feet), hill-top ½ mile N. by E. of Balhennan Farm, Fintry Hills, Stirlingshire (14130). Anal. E.G. Radley; quoted from 'The Geology of the Glasgow District.' (*Mem. Geol. Surv. Scotland*), 1911, p. 142. [Fresh: abundant augite and iron-ore but very little olivine].

A. *Mugearite*. Sill.[3] Druim na Criche, Skye (8732). Anal. W. Pollard; quoted from Harker, 'The Tertiary Igneous Rocks of Skye' (*Mem. Geol. Surv. Scotland*), 1904, p. 263. [Fresh: contains olivine, augite and iron-ore).

[1] Included in Hillhouse type in this paper (see p. 344).

[2] The term 'Galliston type' should no longer be used (see p. 341).

[3] This sill is of Tertiary age. All other analysed rocks except X are of early Lower Carboniferous age.

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The first two analyses of the Markle type (analyses I and II of the Markle Quarry and Hailes Castle rocks) agree very well, but the rock from Burn Crooks Waterworks, Auchineden Hill (analysis III), is considerably poorer in silica, and richer in magnesia and lime. This is due to the groundmass being decidedly more basic than in the type Markle basalt (1913, p. 243). The high ferric oxide in analyses I and II is undoubtedly largely due to decomposition. Analysis III may be taken to represent the most basic varieties which can be included in the Markle type.

There is very close agreement in the analyses (IV and V) of the Dunsapie basalts of Redside and Duncomb Hill, when we consider the fact that titanium was not determined in IV. In an almost fresh rock like that of Duncomb Hill, one would not have expected ferric oxide to be almost twice as abundant as ferrous oxide. Iron-ore grains are however very numerous, and augite phenocrysts rather more sparse than in the type rock.

The Faughlin Burn 'Dunsapie' Basalt (analyses VI) however is very decidedly richer in silica, and poorer in alumina and magnesia, than the Redside rock. The groundmass felspar laths are described as oligoclase-andesine (1916, p. 323). When this feature is coupled with the very low magnesia content, it seems clear that the rock is very different from a typical Dunsapie basalt. It would best be classed probably, as a type intermediate between Markle basalt and mugearite (see p. 351).

Comparison of the Jedburgh analysis (VIII) with the Dalmeny analyses (IX-XI) emphasises the fact that the Jedburgh type is more felspathic than the Dalmeny type and considerably poorer in olivine and augite.

The agreement between the Dalmeny basalts of early Carboniferous age (IX and XI) and that of Millstone Grit age (X) is very marked indeed.

Very close agreement is also seen between analyses XII and XIII the type Hillhouse basalt and Allan's 'Kinghorn' type (which is included in the Hillhouse type in the classification proposed in in this paper.)

As has been pointed out before, the analysis of the 'Galliston dolerite' (XIV) is closer to those of the Hillhouse type (XII and XIII) than those of the Dalmeny type (IX to XI).

All the Mugearite analyses (XV, XVI, XVII, XVIII) agree fairly well, with the exception of XVI. The latter, representing a lava on Lairs, above Lennoxtown, is high in alumina and very

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low in lime content as compared with the others. This very lime lime content " may perhaps be due to albitisation of the felspars, but of this there is no evidence " (1911, p. 143; and 1925, p. 183). The analysis at any rate does not appear to be that of a representative mugearite. The type rock of Skye (analysis A) agrees well with all the Carboniferous examples except XVI.

On comparing the analyses of macroporphyritic and microporphyritic types we find that Markle and Jedburgh basalts are very similar in chemical composition. The Dunsapie type has no very close analogue among the microporphyritic group but the Craiglockhart basalt has a very close chemical resemblance to the Dalmeny basalts. In the macroporphyritic group there is no representative which corresponds chemically to the Hillhouse type of the microporphyritic basalts.

## VI.—Acknowledgements.

In conclusion I must acknowledge with gratitude the debt which I owe to various colleagues on the Geological Survey for instruction and guidance in Carboniferous petrology in the field and in the office, and for discussion and criticism of the views expressed in this paper: in particular I should like to mention Mr. E. B. Bailey and Mr. J. E. Richey. My thanks are also due to Sir John Flett, Director of the Geological Survey of Great Britain, for permission to publish results based on experience gained officially.

Dr. G. W. Tyrrell was kind enough to lend me his slice of the analysed basalt from Duncomb Hill, while Dr. D. A. Allan placed his slices of the Fifeshire 'Kinghorn basalts' at my disposal.

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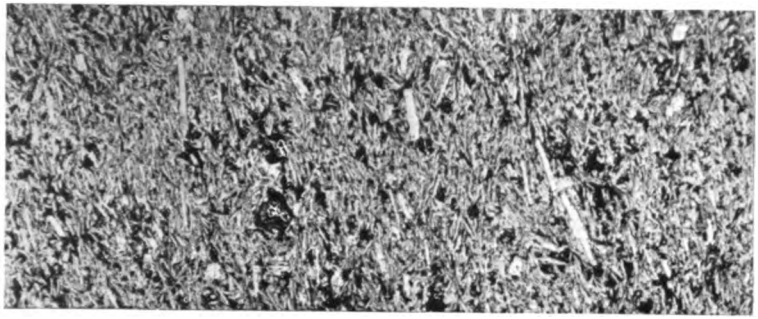

FIG. 1.—MUGEARITE.

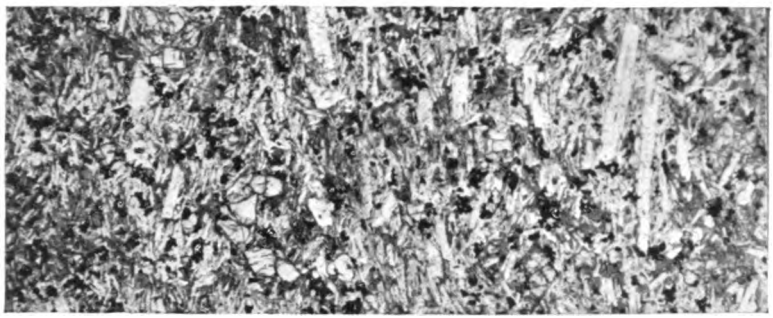

FIG. 2.—JEDBURGH TYPE.

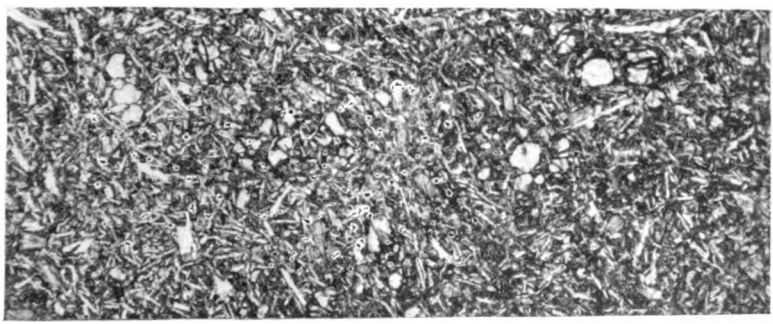

FIG. 3.—DALMENY TYPE.

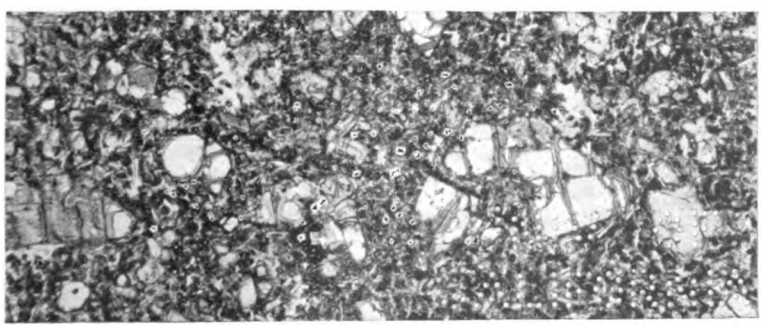

FIG. 4.—HILLHOUSE TYPE.

*Photo. J. Rhodes.*

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## DESCRIPTION OF PLATES.

### *Plate XI.*

Macroporphyritic olivine-basalts.

Fig. 1. *Basalt of Markle Type.* Markle Quarry, Garlton Hills, East Lothian. Slide No. 629.* Magnified 18 diameters (photo No. M1627).† For analysis see table, p. 352.

Large macro-phenocrysts of labradorite, and a few small micro-phenocrysts of olivine (irony pseudomorphs), in a groundmass of plagioclase laths (near labradorite), with some orthoclase and oligoclase, iron-ore, and tiny pseudomorphs which may represent olivine or augite.

Fig. 2. *Basalt of Dunsapie type.* Dunsapie Hill, Edinburgh. Slide No. 12013. Magnified 18 diameters (photo No. M1630). Not analysed.

Macro- and micro-phenocrysts of pale-brownish augite, olivine (largely fresh), and labradorite (only microporphyritic felspar seen in photograph), in a rather coarse groundmass of plagioclase (near labradorite) with little prisms and granules of augite, serpentinised olivines, a little analcite, and sporadic tiny scraps of late-formed biotite.

Fig. 3. *Basalt of Craiglockhart type.* Craiglockhart Hill, Edinburgh. Slide No. 13571. Magnified 18 diameters (photo No. M1631). Not analysed.

Macro- and micro-phenocrysts of pale-brownish augite and of serpentinised olivine, in a groundmass of plagioclase (near labradorite), augite, serpentinised olivine, and iron-ore.

### *Plate XII.*

Mugearite and microporphyritic olivine-basalts.

Fig. 1. *Mugearite.* Railway cutting east of East Linton Station, East Lothian. Slide No. 11301. Magnified 18 diameters (photo. No. M1628). Not analysed.

* Numbers refer to slides in Scottish collection of H. M. Geological Survey.

† Numbers refer to photomicrographs in collection of H. M. Geological Survey.



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Fine-grained rock with good flow-structure of abundant oligoclase laths, some small irony pseudomorphs after olivine, decomposed iron-ore grains, and possibly a little pseudomorphed augite or olivine wedged between the felspar laths.

Fig. 2. *Basalt of Jedburgh type.* Little Caldon neck, north of Kilpatrick Hills, Stirlingshire.

Slide No. 13303. Magnified 18 diameters (photo. No. M1632). For analysis see table, p. 352.

Abundant parallel lathy micro-phenocrysts of plagioclase (near labradorite) and some microphenocrysts of fresh olivine, in a groundmass of lathy plagioclase (near labradorite) and micro-ophitic purple augite, with some iron-ore.

Fig. 3. *Basalt of Dalmeny type.* Quarry 230 yards south of Dalmeny Church, Linlithgowshire. Slide No. 25062a. Magnified 18 diameters (photo. No. M1634). For analysis see table p. 352.

Abundant micro-phenocrysts of olivine (largely fresh) and some of pale-brownish augite, in a groundmass of lathy plagioclase (near labradorite) and little sub-ophitic to almost idiomorphic augite granules, with some iron-ore. The augite micro-phenocrysts frequently enclose the ends of groundmass felspar laths in sub-ophitic fashion.

Fig. 4. *Basalt of Hillhouse type.* Hillhouse Quarry, Mid-Lothian. Slide No. 1670b. Magnified 18 diameters (photo. No. M1629). For analysis of another specimen from the same quarry, see table, p. 353.

Abundant micro-phenocrysts of olivine (largely fresh) and of purplish-brown augite (the latter relatively somewhat smaller), in a groundmass rich in a granular augite and iron-ore, but with a little lathy plagioclase (near basic labradorite), and a small proportion of analcite or glass.

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| | UNDMASS. | | REMARKS. |
|---|---|---|---|
| MACROPORPH OLIVINE BASALTS | LS. | STRUCTURES. | |
| MARKLE TYP | n-ore. livine, apa- ' chlorite.' Ratio often Type. | Usually non-ophitic but sub-ophitic and ophitic structures are occasionally found. Flow structure of felspar laths is uncommon. | Felspar phenocrysts may range from about labradorite to bytownite. In more alkaline varieties, oligoclase and orthoclase may be present in the groundmass in considerable amount. |
| DUNSAPIE TY | -ore. ite, biotite, chlorophae- Ratio often khart Type. | Usually non-ophitic but sub-ophitic and ophitic structures are possible. Flow structure of felspar laths is very uncommon. | Felspar phenocrysts may range from about labradorite to bytownite. |
| CRAIGLOCKHA TYPE | -ore. te ' etc | Usually non-ophitic but sub-ophitic and ophitic structures are sometimes found. Flow structure of felspar laths is very uncommon. | |
| MICROPORPHY OLIVINE-BASA | | | |
| JEDBURGH TY | -ore. , apatite, lende, glass neny type. | Either non-ophitic (' microlitic ') or ophitic. Good flow structure of felspar laths is characteristic. | Intermediate between Dalmeny basalt and mugearite. |
| DALMENY TYP | -ore. orophaeite, | Usually non-ophitic or sub-ophitic. Flow structure of felspar laths is uncommon. | Sporadic felspar phenocrysts (if present) approximate to labradorite. Some varieties are coarse enough to be on border-line of olivine-dolerites. |
| HILLHOUSE TY | ittle labra- abundant. | Usually non-ophitic. | A passage type between olivine-basalt and limburgite or monchiquite. |
| MUGEARITE | hornblende, orophaeite, present but ons. | Usually non-ophitic. Flow structure of felspar laths is almost always very pronounced. | Non-porphyritic rocks are most abundant. Felspar phenocrysts if present may have a wide range of composition. Mugearites are typically very fine-grained. |

* P = Present in al

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No. XIV.—The Igneous Geology of Central Ayrshire. By V. A. Eyles, B.Sc., J. B. Simpson, B.Sc., and A. G. MacGregor, M.C., B.Sc.

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## INTRODUCTION.

DURING the past few years the Geological Survey has been engaged in a revision of the post-Silurian geology of Central Ayrshire. While most of the area to be described was revised by the authors, acknowledgment must be made to Mr. J. E. Richey and Mr. E. M. Anderson who mapped, respectively, the district between Maybole and Dailly, and the Troon–Symington–Craigie district.

It is now possible to summarise the igneous geology of this area, and the following account incorporates the general results of the re-survey, and includes a number of new rock analyses. We are indebted to Sir John S. Flett, Director of the Geological Survey of Great Britain, for permission to present this paper to the Glasgow Geological Society. We have also to thank Mr. E. B. Bailey, under whose supervision the work was carried out, for assistance more particularly in regard to the petrography of the Permian intrusions. The rock analyses have been made by Mr. E. G. Radley, and Mr. B. E. Dixon.

The area here termed ' Central Ayrshire ' is bounded, roughly, *on the north* by a line from Troon through Mauchline to a point about three miles east of Sorn, *on the south* by a line passing east from Girvan for about fourteen miles, and thence north-east to New Cumnock, *on the east* by a line running north from New Cumnock, as far as the Sorn–Muirkirk road, and *on the west* by the Firth of Clyde. The major portion of this area is included within 1 inch Sheet 14 of the Geological Survey (Scotland), 1868, but the marginal parts include portions of the following 1 inch to the mile Geological Survey (Scotland) Maps: Sheet 8 (1893); Sheet 13 (1902); Sheet 15 (1870); Sheet 22 (1870).[1] The dates indicated are those of the publication of the old hand-coloured geological editions. Almost the whole area, however, is included in Sheet 16 of the ¼ inch to the mile Geological Survey map (colour printed), 1904. In so far as the igneous rocks are concerned, the latter differs little from the older 1 inch maps.

The first comprehensive account of this district was furnished by the brothers Geikie and B. N. Peach (1869a).[2] Since then our knowledge of the igneous rocks has been amplified by other workers. We may refer especially to the writings of Sir A. Geikie,

[1] A new edition (colour-printed) has been published since the reading of this paper. See bibliography.

[2] Dates in brackets refer to bibliography, p. 385.

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of Mr. John Smith, of Dr. G. W. Tyrrell, and to the 'Summaries of Progress of the Geological Survey.' In the sequel the igneous rocks are described in approximately chronological order.

## I. Lower Old Red Sandstone Period.

Igneous rocks of this age are well represented in Central Ayrshire by lavas and intrusions, including volcanic necks.

(*a*) *Lavas and Ashes.*

The most important outcrops of lava occur:

(1) To the south and south-west of Ayr, round about Brown Carrick Hill.

(2) In a belt of much faulted and folded country running south-west from Dalleagles by Dalmellington to the district near the Water of Girvan, above Straiton.

All the lavas overlie, or are intercalated with, the topmost beds of the Lower Old Red Sandstone sediments of the district. No sediments of this age have been found overlying the Ayrshire lavas, although well developed in this position in other parts of Scotland, notably in Strathmore and in Lanarkshire.

In type the lavas are basalts and basic andesites (see Analysis I, p. 384); they often contain conspicuous porphyritic felspars, and are usually very decomposed. It has been found possible to separate an olivine-rich variety, without porphyritic felspars, which occurs only at, or near, the base of the lava succession, though not invariably present (Eyles and MacGregor, 1926, pp. 94-95). This fact has proved of assistance in the mapping of some of the more disturbed occurrences.

The field characteristics of the lavas are too well known to need description here (Tyrrell, 1916, pp. 65-69). They are closely similar to those of Lower Old Red Sandstone lavas in other parts of Scotland.

Dr. Tyrrell (1916, pp. 64 and 68) has regarded certain detached outcrops of lava as inconstant lenticular volcanic masses occurring at different horizons in the Old Red Sandstone. His conclusion is doubtless based on the position in which these outcrops are shown on the old 1 inch geological maps. The revised mapping however shows that it is improbable that any of these detached outcrops occupies a stratigraphical position lower than that of the lowest flows of the main lava pile forming the Carrick Hills.

Thus, the lavas in Maidenhead Bay (1 inch Sheet 14, between Barwhin Point and Turnberry Shore) and at Turnberry (1 inch

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Sheet 13; See Fig. 34) have been proved to occupy the same stratigraphical position as those of the Brown Carrick Hill area. They have been let down by a fault which runs north-east across Turnberry Golf Course into Maidenhead Bay, to pass under sea west of Barwhin Point. East of this the same lavas outcrop on the shore at Culzean Bay for a mile, until interrupted by a north and south fault. On the other side of this fault an outcrop,

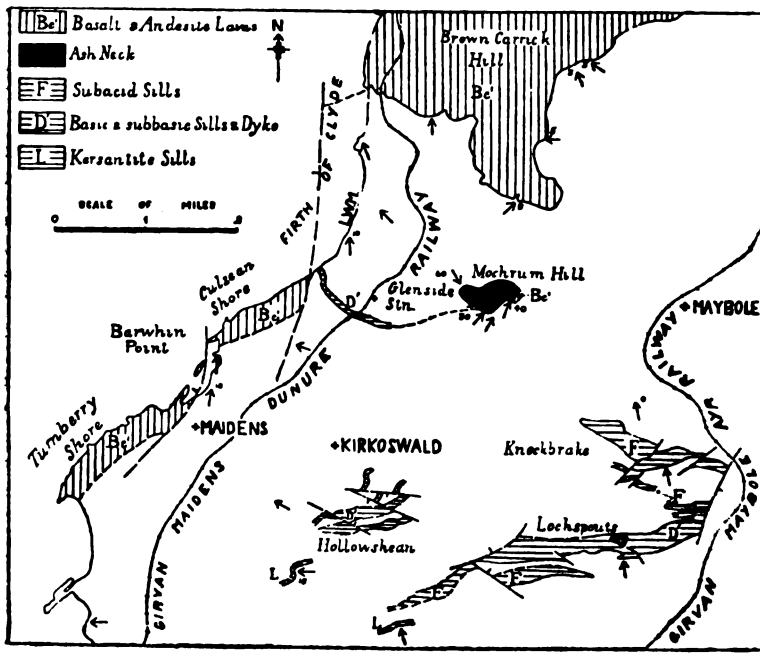


Fig. 34.—Sketch-map to illustrate the nature and distribution of the igneous rocks of Lower Old Red Sandstone age, west of Maybole, Ayrshire.
(*Dip of strata indicated by arrows*).

previously mapped as lava, proves to be a broad dyke, and is, in fact, the continuation of an exposure on the shore, already recognised as intrusive. This dyke is now, on petrographical grounds, regarded as being of Lower Old Red Sandstone age.

Again, inland farther east, three small detached outcrops of 'lava' are shown on the old 1 inch Sheet 14, south of Dalrymple. These are now found to consist, in the main, of an intrusive pink felsitic rock, probably of Lower Old Red Sandstone age. There

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is, however, some lava there, similar in type to, and probably occupying much the same stratigraphical position as, the non-porphyritic basal flows of the Carrick Hills. A small patch of igneous rock nearby, previously mapped as intrusive 'felstone,' is also, in fact, lava of this type.

Two outcrops (see Fig. 34) shown on the old map as lava, one 1½ miles south, and the other 4 miles south-west of Maybole are now regarded as intrusions of Lower Old Red Sandstone age. This was first suggested by Dr. G. W. Tyrrell (1916, p. 69) some years ago, in a paper which also gives a detailed description of the petrography of these and other neighbouring intrusions, and of the lavas of the Brown Carrick Hill area.

Before passing on to the volcanic necks of Lower Old Red Sandstone age, brief mention may be made of an interesting occurrence of bedded volcanic ash associated with the lavas. Bedded ash of this age is comparatively rare in Central Ayrshire, and this example, which occurs at the north end of Maidenhead Bay, underlies the lowest lava of the exposure. Its particular interest lies in the fact that it contains numerous fragments, conspicuous by their white weathered surfaces, of a lava which is apparently more acid than any type found among the Lower Old Red Sandstone extrusive rocks of Central Ayrshire. Acid types are, however, well represented among the intrusions of this age.

(*b*) *Volcanic Necks.*

The supposed absence, in Central Ayrshire, of any exposure which could definitely be regarded as forming part of a volcanic vent of Lower Old Red Sandstone age has been commented on by Sir A. Geikie (1897, vol. i, pp. 332, 335) and by Dr. G. W. Tyrrell (1916, pp. 68-69). As a result of the Survey revision we now believe that there are probably three volcanic vents of this age, in the area under consideration.

The largest and best exposed of these forms Mochrum Hill (see Fig. 34), a prominent landmark 2¼ miles west of Maybole. Sir A. Geikie (1869a, pp. 12-13) was originally of the opinion that the major portion of this hill was formed of bedded ash, and that it included a flow of 'porphyrite' lava. At a later date (Geikie, 1892, p. 88), he mentioned Mochrum Hill as a possible neck; but, as we have seen, he did not develop this suggestion in his 'Ancient Volcanoes.' Recently the woods which covered the hill have been extensively cut down, and this has laid bare a number of hitherto unnoticed exposures. It has become clear that almost the entire

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hill, whose maximum diameter is nearly ¾ mile, represents the pipe of an extinct volcano. The vent is largely filled with rock ranging from rather fine-grained very sandy ash to coarse agglomerate composed of big masses of lava with very little matrix. In some cases at least, the included lava is of a type which can be matched among the lavas of the Carrick Hills to the north. There appears to be no evidence that a cap of lava exists on the top of the ashes, as is shown on the old 1 inch map, but exposures at the east end of the neck indicate that this side of it is largely filled with vent lava, rather than ash. At the south-east end of the hill a quarry has been opened within the vent in typical old Red Sandstone lava. The steep south side of the hill is partly composed of sediments, and in two or three places towards the top the actual edge of the vent is exposed, showing a transgressive junction between ash and sediment. At the base of the north-west end of the hill a small exposure shows a few feet of red sandy mudstone underlying lava, and dipping steeply in towards the hill. This may well be part of the broken material of the wall of the vent on that side.

As to the evidence for the age of the neck, the agglomerate filling it is composed entirely of rocks of Lower Old Red Sandstone type, there being a complete absence of any of the material characteristically found in the New Red Sandstone (and Carboniferous) necks so well known in Ayrshire. Conclusive evidence, however, is afforded by the fact that a dyke to which, on petrographical grounds, a Lower Old Red Sandstone age may safely be assigned, cuts the vent near its edge on the south-west side. This dyke is possibly connected with one seen on the shore to the west near Culzean Castle (see p. 369 and Fig. 34), directed towards the neck.

A second neck, almost certainly of the same age, occurs 2½ miles south-west of Dalmellington and about ½ mile north-north-east of Little Shalloch. Exposures are poor, but an outcrop, previously treated as intrusive 'felstone' of Old Red Sandstone age, has now been shown to include an area of ash 200 yards in diameter. This ash stands up as a prominent knoll.

The third Lower Old Red Sandstone neck is shown in the extreme north-east corner of the old 1 inch Sheet 14 on the farm of Auchinlongford, 3 miles north-east of Sorn. It is there marked as a New Red Sandstone vent in association with an acid intrusion. Examination has shown that this intrusion is undoubtedly of

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Lower Old Red Sandstone type, as are the materials forming the agglomerate of the vent.

(*c*) *Other Intrusions.*

Numerous intrusions of Lower Old Red Sandstone age occur in Central Ayrshire. They are mostly concentrated in two areas:—

(i) The faulted belt of country running south-west from Dalleagles by Dalmellington to Glenalla Fell, beyond Straiton.

(ii) The area of Old Red Sandstone sediments centred about Maybole.

Most of these intrusions may be classed as sills, but some dykes occur.

*Area* (*i*). In this district the larger intrusive masses, which are mostly sills or laccoliths, often form prominent hills, such as Turgeny, Glenalla Fell, and Garleffin Fell; they are largely composed of reddish acid biotite-porphyrite, but felsite and plagiophyre are also found. Some, and possibly all, of these intrusions (shown with an orange colour and lettered 'F' on the published maps), are younger than some, at least, of the lava-flows of the district. Conglomerates, ashes and agglomerates, however, which are associated with these lavas, contain fragments of types closely allied to the acid intrusions.

South of Dalmellington Mr. Simpson finds evidence to suggest that some of these acid intrusions are later than the great north-east-trending Southern Upland Fault, and the minor faults parallel to it. On the other hand the intrusions at Turgeny, at Glenalla Fell, and near Garleffin Fell are almost certainly affected by north-east faulting.

A few smaller sills and dykes are only known to cut sediments *older* than the lavas. They are kersantites resembling the kersantite dykes of Wigtownshire.[1] A prominent example is a sill which forms an arcuate outcrop about 1 mile south-south-east of Turgeny.

A number of minor intrusions, mostly dykes, are found cutting either the lavas or the large biotite-porphyrite laccolith, which lie a little west of Knockdon (4 miles south-east of Straiton). Those in the lavas include biotite- and hornblende-porphyrites, while among the dykes cutting the biotite-porphyrite laccolith we find fine- and very coarse-grained olivine-basalts of Lower Old Red Sandstone types.

[1] Read, H. H. 'The Mica-Lamprophyres of Wigtownshire.' *Geol. Mag.* LXIII, 1926, p. 425.

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An intrusion of quartz-dolerite, with crystals of fresh diopsidic augite, occurs at the Black Hill of Knockgardner, 2 miles south-west of Straiton, in Lower Old Red Sandstone sediments. In type this rock stands rather by itself, but it is thought that it may be of Lower Old Red Sandstone age. In addition, on the sides of Knockinculloch Hill, 3½ miles south-south-east of Crosshill, there are two exposures of fresh quartz-dolerite, also believed to be of Lower Old Red Sandstone age. They possibly form part of a sill or sills, and are intruded at about the base of the Lower Old Red Sandstone. It may conveniently be noted here that certain sills and a few dykes farther south, in 1 inch Sheet 8, notably a big sill cutting Lower Old Red Sandstone sediments on Daljedburgh (or Jerburgh) Hill, three miles north-east of Barr, are composed of basalt or dolerite containing quartz.

It is not certain whether the quartz in some of these intrusions is primary (juvenile) or secondary. This uncertainty applies to many of the intrusions which are here described as 'quartz-bearing' dolerites or basalts. In those described as 'quartz-dolerites' the quartz is thought to be definitely juvenile and of magmatic origin.

Extensive baking (locally very severe) has been produced in the country rocks (mainly Lower Old Red Sandstone sediments) by an intrusive complex near Knockdon. The adjacent lavas have also been somewhat altered, and frequently contain epidote. The intrusive igneous types include coarse-grained rocks allied to quartz-diorite, together with acid porphyrites, and fine-grained reddish types which closely resemble the plagiophyre and quartz-plagiophyre intrusions of the Maybole district (Tyrrell, 1916, pp. 78-79). The most interesting feature is the fact that parts of the intrusive complex are extremely rich in dark-bluish tourmaline. Tourmaline of pneumatolytic origin is also found in the altered country rocks (MacGregor, 1928c, p. 58).

*Note.*

At Tincorn Hill, north-east of Sorn (1 inch Sheet 14) there is another area where Lower Old Red Sandstones have been highly baked by dioritic intrusions of Lower Old Red age; earlier minor intrusions have also been contact-altered. These phenomena are connected with the intrusion of the Distinkhorn granodiorite-diorite complex south-east of Darvel, which will be described with its accompanying contact-metamorphism in the forthcoming Geological Survey Memoir which describes 1 inch Sheet 22.

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*Area (ii)*. Most of the sills of this district have been described by Dr. G. W. Tyrrell (1916, pp. 69-71, 76-82). He records olivine-dolerites, quartz-dolerites[1] and also certain acid to intermediate types for which he has proposed the term 'plagiophyre.' The majority of these intrusions occur at horizons well down in the sediments. To the north-east of Maybole, however, near Dalrymple, a felsite mass appears to cut basal lavas (see p. 364).

A faulted quartz-bearing doleritic sill of Lower Old Red Sandstone type is intruded in sediments below the lavas at Guiltreehill, 2½ miles south of Dalrymple. Owing to a colourist's error it has been shown as a band of ash on the hand-coloured 1 inch map (Sheet 14) of 1868.

Lamprophyres (kersantites) are represented by two sills near the farms of Low Craigenton and North Threave, about 2 miles south of Kirkoswald.

The intrusion on the shore at Culzean Castle and its inland continuation hitherto mapped as a lava, is formed of a somewhat variable olivine-basalt. Quartz is present in some of the slices, but is almost certainly of secondary origin.

## II. Calciferous Sandstone Period.

The next manifestation of igneous activity in Central Ayrshire occurred in Calciferous Sandstone times. It was of very minor importance in the area here described, compared with the extensive volcanic outpourings of this age in North Ayrshire and elsewhere in Scotland.

*(a) Heads of Ayr Vent and Greenan Castle Ash.*

First may be mentioned the bedded ash of Greenan Castle, (Fig. 35) on the shore 2½ miles south-west of Ayr, and the Heads of Ayr volcanic neck, 4 miles south-west of Ayr, which, probably, was the source of the Greenan ash.

As long ago as 1869 Sir A. Geikie (1869a, p. 17) recorded the occurrence at Greenan Castle of 'dolerite tuff,' which he stated to be partly interbedded with the Cementstone Group, and partly intrusive, the remains of a contemporaneous neck. It seems clear, however, as Dr. G. W. Tyrrell (1920, p. 344) has pointed out, that the whole of the Greenan ash outcrop, both on the foreshore and in the cliff below the Castle, is an intercalation, some 60 to 70 feet thick, near the top of the Cementstone Group.

[1] In some of these dolerite or basalt sills the quartz may be secondary; in others it is almost certainly juvenile (primary).

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Sandstone is seen to pass conformably under the base of the bedded ash, while the topmost beds of the latter pass upwards into a series of somewhat ashy shales and cementstones. Minor faulting complicates the outcrop on the foreshore and tends, in places, to give the false impression of a transgressive rather than an intercalatory junction between ash and sediment.

The Heads of Ayr vent, which forms a fine sea-cliff about half a mile long, was also recognised as such by Sir A. Geikie, and he regarded it as of the same general age as the Greenan ash. Dr. G. W. Tyrrell (1920, pp. 356-57, 359-360) adopts this view, with the qualification that the Heads of Ayr neck is somewhat the earlier. Our own conclusion is that the Heads of Ayr neck supplied the Greenan ash.

To begin with, it may be pointed out that, on petrographical grounds, the neck can scarcely be of any other age than Carboniferous or New Red Sandstone. So far we are on common ground with Dr. Tyrrell. We shall now proceed to the evidence of inter-relation between the Heads of Ayr vent and the Greenan ash.

Dr. Tyrrell thought that the Heads of Ayr ash, at each end of the exposure, extended beyond the limits of the neck, to overlie sediments on a distinctly lower horizon than those associated with the Greenan ash. He also pointed to differences in the nature of the ashes at the two localities. In regard to the supposed contemporaneity of some of the Heads of Ayr ash with adjoining sediments, it can only be said that careful examination seems to demonstrate vertical junctions in every case. In comparing the Heads of Ayr and Greenan ashes, certain significant points of resemblance, which had not been noted by Dr. Tyrrell at the time of writing his paper quoted above, can now be demonstrated. These are that both ashes contain lumps or fragments of:—

(1) carbonated peridotite;
(2) fossil wood, replaced by calcite;
(3) recognizable Old Red Sandstone lavas.

In spite of a careful search we have been unable to find, in the Greenan ash, any fragments of lava—such as the 'mugearite' mentioned by Dr. Tyrrell[1]—of distinctive Carboniferous type.

It will be seen then, that these points of similarity support the

[1] *Op. cit.* 1920, pp. 348, 360. Note: Dr. Tyrrell has since expressed to me, by letter, his doubt as to whether these 'mugearites' are not really Old Red Sandstone lavas. V.A.E.

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view that the two ashes are at least roughly contemporaneous. To sum up:—The Greenan ash is interbedded near the top of the Cementstone Group. No other interbedded ash is known in the shore section of this group. The Heads of Ayr ash, about 1½ miles distant, fills a neck that cuts the lower part of the Cementstone Group. The ashes in the two exposures have strong points of resemblance. It would appear, therefore, that the Heads of Ayr neck has supplied the Greenan ash, and that the two are of exactly the same age.

It is very interesting to note that the Greenan ash has two points in common with the ashes filling necks of undoubted Permian (New Red Sandstone) age in Ayrshire. These are the occurrence of lumps of carbonated peridotite and of big crystals of alkali-felspar (Eyles and MacGregor, 1926, pp. 99-100).

At the Heads of Ayr small xenolithic intrusions of nepheline-bearing monchiquitic basalt cut the ash. These intrusions carry xenoliths of peridotite (Tyrrell, 1920, pp. 350-51, 360) similar to the carbonated peridotite nodules occurring both in the neck ash and in the bedded ash of Greenan Castle.

As to the age of the intrusions, Dr. Tyrrell (1920, pp. 360-1) suggested, somewhat doubtfully, that they were later than the neck itself, and might represent a slight re-awakening of the focus during the Permian volcanic episode. Although, in Ayrshire, similar intrusions are usually associated with Permian vents, rocks with many Permian characteristics have been described from the Calciferous Sandstone of East Lothian by Dr. F. H. Hatch[1] and Mr. E. B. Bailey,[2] from the Carboniferous Limestone of Ayrshire by Mr. G. V. Wilson,[3] and from the Carboniferous Limestone of Fife (Largo Law) by Mr. D. Balsillie.[4] It appears therefore, at least as probable that the small intrusions at the Heads of Ayr may be contemporaneous with the neck, i.e. of Calciferous Sandstone age.

[1] 'The Lower Carboniferous Volcanic Rocks of East Lothian,' *Trans. Roy. Soc. Edin.*, XXXVII, 1892, pp. 116-118.

[2] In 'The Geology of East Lothian,' (*Mem. Geol. Surv. Scotland*), 2nd Ed. 1910, pp. 3, 99, 100, 105-113. *See also* E. B. Bailey in 'The Geology of the Glasgow District,' (*Mem. Geol. Surv. Scotland*), Revised Ed. 1925, p. 152, footnote (3).

[3] 'Preliminary Notes on Volcanic Necks in North-West Ayrshire,' *Trans. Geol. Soc., Glasgow*, XVI, 1916, pp. 93, 97 (Neck no. 20).

[4] 'Further Observations on the Volcanic Geology of East Fife,' *Geol. Mag.*, 1923, pp. 530-42.

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(*b*) *Lava with Lateritic Weathering.*

In addition to the above-mentioned occurrences of Calciferous Sandstone volcanic rocks, a basalt lava of this age has been noted in the north-east corner of 1 inch Sheet 14. Two exposures occur in the River Ayr east of Sorn, one near the farm of Upper Heilar, the other at the farm of Hole. This latter occurrence has been described previously (Simpson, 1923, p. 79). It is of particular interest owing to its having been contemporaneously weathered into a bauxitic clay of a type commonly found associated with the Millstone Grit lavas of North Ayrshire (Wilson, 1922). A partial analysis of the material gives $SiO_2$, 40.65% and $Al_2O_3$, 36.77%. The clay thus just falls within the limits of the term ' bauxitic ' as defined by G. V. Wilson (1922, p. 6).

## III. Millstone Grit Period.

(*a*) *Lavas and Lateritic Clays.*

After the close of Calciferous Sandstone times there is no evidence of igneous activity in Central Ayrshire until the Millstone Grit Period.

It has long been known (Geikie, J. and A., 1872, pp. 17-21, 23-24) that volcanic rocks occur at this horizon in North Ayrshire, and in recent years much attention has been drawn to them owing to the associated deposits of Ayrshire Bauxitic Clay. It has since (Eyles, Summary of Progress, 1924, pp. 97-98) been shown that lava of this age occurs throughout a considerable area in the north-west part of 1 inch Sheet 14. Along the northern margin of the area now being described (in 1 inch Sheet 22) the outcrop of the Millstone Grit lavas has been traced, with interruptions due to faulting, from the coast at Barassie, inland as far east as a point about 2½ miles north-north-east of Mauchline. The lavas are continued southwards under the Coal Measures of the north-west part of the Central Ayrshire coal basin, where their occurrence has supplied a useful datum line in mineral boring. They reappear at the surface south of the River Ayr, and their southern outcrop (see Fig. 35) extends from Longhill Point,[1] on the coast,

[1] Note: Dr. Tyrrell (1920, p. 345), has suggested that the basalt at Longhill Point is a sill. The fact that its decayed upper part is shaly, with flattened residual felspars, and is overlain by hard mottled clay containing volcanic detritus, leaves no room for doubt that it is in fact lava. That it is of Millstone Grit age is inferred from a combination of stratigraphical and petrographical evidence.

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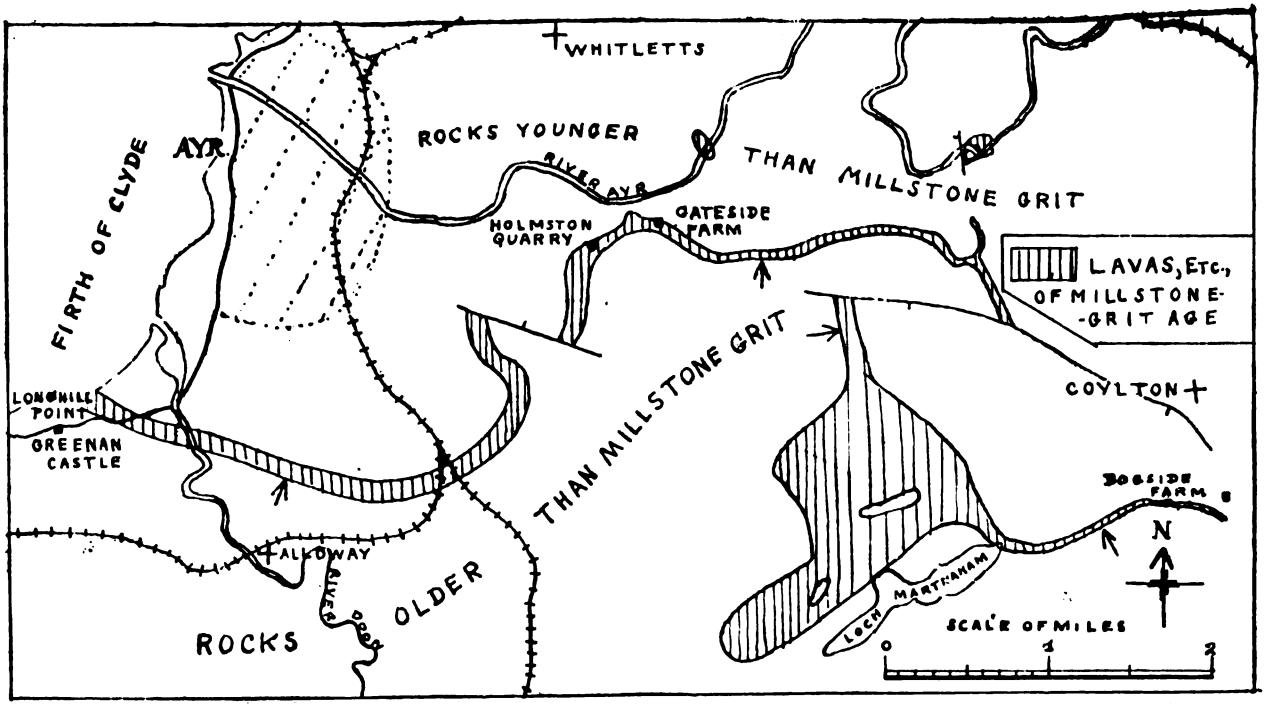


Fig. 35.—Sketch-map showing the outcrop of Millstone Grit lavas and associated volcanic detrital rocks, south of the River Ayr.
(*Dip of strata indicated by arrows*).

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inland as far as Bogside farm, three quarters of a mile south of Coylton.

The maximum development of these volcanic rocks occurs in the west, in the neighbourhood of Troon, where a bore at Gailes, 3 miles to the north, penetrated over 480 feet of lavas. In the southern and eastern parts of the area the total thickness of lava is often less than 60 feet. North of Loch Martnaham however, where, as shown in Fig. 35, there is a local broadening of the outcrop, the thickness of the lavas appears to be approximately 180 feet. There are in this neighbourhood a number of exposures of olivine-basalt which, both in the field and under the microscope, has the appearance of Millstone Grit lava. A study of the local geology however, including information derived from boring, shows that, in part, these lavas to the north of Loch Martnaham rest on upper Calciferous Sandstone sediments. Without going into detail it may be stated that the most likely explanation of this fact is that Millstone Grit lava, owing to local erosion, here transgresses on to the Calciferous Sandstone. The complete removal of the Carboniferous Limestone Series at this point is not difficult to imagine, since it is known to be exceptionally thin hereabouts (200 to 300 feet).

South-east of a line running approximately from Mauchline to Coylton, volcanic rocks seem to be entirely absent from the Millstone Grit.

The lavas are uniformly olivine-basalts, and they appear in nearly every exposure to have been subject, in greater or less degree, to contemporaneous weathering of the same type as that which altered the Millstone Grit lavas of North Ayrshire (Wilson, 1922, pp. 2, 8, 13-16). In some cases there are, associated with the lavas, beds comparable to the Bauxitic Clay of North Ayrshire. Three samples were analysed (see analyses II, III and IV, p. 384) from the most promising locality. Unfortunately they appear to contain too much iron and other impurities to be of value as refractories.

## IV. Permian (New Red Sandstone) Period.

The Ayrshire New Red Sandstones (which mainly overlie the lavas of Mauchline) have been variously styled Permian and Trias; we take it as demonstrated that they belong to one of these periods. In most of the literature dealing with the igneous rocks the term Permian has been employed (1897, vol. ii, pp.

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55-56). In what follows, this practice will be adopted merely on the ground of convenience and without any suggestion that the stratigraphical position is settled.[1]

(*a*) *Lavas, Necks and Smaller Intrusions.*

Since Sir A. Geikie (1866, p. 243, and 1897, vol. ii, pp. 53-67) described the Permian lavas and necks of Ayrshire, the main advances have been due to Dr. Tyrrell's petrographical researches (1912, pp. 125-27).[2] He has shown that the lavas range from basic to ultrabasic (see analyses V and VI, p. 384) and sometimes contain nepheline—a mineral not recorded from the Tertiary lavas of the Hebrides.[3] Another distinctive feature, unknown in Tertiary lavas, is the frequent occurrence of porphyritic augite in association with abundant olivine.

The petrography of most of the igneous blocks, and of the intrusions, in the necks which are classed as Permian, recalls very closely that of the lavas.[4] Augitic monchiquite is a characteristic ultrabasic type in the necks, and it also occurs at some distance from the latter as small sills and dykes, too small to show in Fig. 36. It corresponds in most features with certain ultrabasic flows among the lavas. There is only one important character which has not been matched among the lavas, namely the frequent occurrence in the monchiquites of carbonated peridotite nodules and of large phenocrysts, or cognate xenocrysts, of anorthoclase (Eyles, 1924, p. 472) biotite, hornblende (Tyrrell, 1912, p. 78, and 1920, p. 359) and apatite. The presence of large apatite phenocrysts in monchiquite and camptonite has already been recorded from Western Scotland,[5] and from Finland.[6]

[1] *Compare* Horne, J., and J. W. Gregory, 'The Annan Red Sandstone Series of Dumfriesshire,' *Trans. Geol. Soc. Glasgow*, XV, 1916, pp. 374-386; and R. L. Sherlock, 'A Correlation of the British Permo-Triassic Rocks' Part I, *Proc. Geol. Assoc.* XXXVII, 1926, pp. 47-52, 62, Part II, *Proc. Geol. Assoc.*, XXXIX, 1928, p. 91 (Note).

[2] Since this paper was written Dr. Tyrrell has published a new and important contribution to our knowledge of the Permian lavas and necks of Ayrshire (1928a, pp. 259-294).

[3] Nepheline has been recorded from only two proved Tertiary rocks in the Hebrides—both intrusions.

[4] A few blocks and neck-intrusions resemble the hypabyssal rocks forming the larger sills; they are dealt with below in the account of these sills.

[5] Flett, J. S., in 'The Geology of Colonsay and Oronsay with part of the Ross of Mull,' (*Mem. Geol. Surv. Scotland*), 1911, p. 44.

[6] Hackmann, V., 'Über Camptonitgänge im mittlerem Finnland,' *Bull. de la Comm. Géol. de Finlande*, No. 42, 1914, pp. 10, 11 and figure.

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Fragments and blocks of carbonated peridotite are also to be found in the agglomerate of some of the necks (Geikie, 1897, vol. ii, p. 58; and MacGregor, 1925, p. 95).

In arriving at a Permian age for these Ayrshire necks, we are guided by three considerations. The necks cut all divisions of the Carboniferous and in some cases even the Permian lavas (north of Tarbolton and near Ochiltree). They are unknown in the sandstones above these lavas. Petrographically their contents resemble the *latter* and differ from *Tertiary* lavas that are known in the Hebrides and the North of Ireland.

(*b*) *Larger Sills.*

The Central Ayrshire sills that are regarded as of Permian age show a considerable range of composition and texture. Among the larger occurrences (shown on Fig. 36) three broad groups have been found to be distinguishable in the field. It is on the field characteristics, including observed association of various types, supplemented by microscopic study, that the classification indicated on the map (Fig. 36), is based.

Much valuable work on these Ayrshire sills has been carried out by Dr. G. W. Tyrrell, who has described and classified all the main occurrences [*See especially* Tyrrell, 1912, pp. 69-80 and 120-125, and 1923, pp. 249-260]. He considers most of them to be of Permian age. In many cases he has demonstrated the presence of nepheline and other alkaline minerals, while in others he has realized that alkalinity is no more marked than in many of the Tertiary basalts of the Hebrides. All these important points, as well as much petrographic detail, have been confirmed during the Survey investigation.

The table on p. 387 amplifies the classification used for the map, and indicates its relation to the types and rock series of Dr. Tyrrell.

Before dealing briefly with each group in turn a few general features of the table will be mentioned. Within Group 1 and Sub-group 2*a* respectively the cut specimens show every transition from the less mafic to the more mafic types, and even within one intrusion or intrusive complex variation is found which covers much of the range within one or other group. Evidence will be given below which points to a close genetic relation between Groups 1 and 2a. A general feature of the classification is the progressive decrease of alkalinity on passing from Group 1 (considered as a whole) through Sub-group 2a (also viewed

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generally) and on to Sub-group 3b. Apart from late veins there is little variation in type *within* each of the sub-groups 2b, 2c, 3a, and 3b.

*Group* 1. Olivine-rich ultra-femic theralites or essexites are characteristic members of this group. Such rocks have been called kylites by Dr. Tyrrell (type locality Benbeoch). Within any big mass, varieties both more and less mafic than kylite are usually found. Abundance of fresh olivine, the purple colour of the augite, the frequent presence of nepheline, the subordination of analcite, and the very small part played by hornblende, are the main mineralogical features of the suite as a whole.

Among the larger sills may be mentioned those which form the Craigs of Kyle (see analysis VII, p. 384), Kilmein Hill and High Mount.[1] Intrusions of the kylite suite cut rocks ranging from Calciferous Sandstone sediments to Productive Coal Measures, and possibly to Barren Red Coal Measures (Skares sill, including Garlaff and Knockterra exposures). In two cases mining information proves that sills of the kylite suite (Benbain and Craigmark Hill) cross important faults in the Coal Measures. In two other cases sills belonging to the suite (Craigs of Kyle; and Green Hill, Knockgulderon) have their outcrops interrupted by 'Permian,'[2] necks in a manner which makes it almost certain that the necks are later than the sills. Fragments of igneous rocks belonging to the suite have been found in three Permian necks (Green Hill, Waterside; the Burnhead neck near Corbie Craigs; and Helenton Hill, 4 miles east of Troon). Dr. Tyrrell found an intrusion of essexite of Crawfordjohn type (a typical member of the suite) in the Permian neck known as Carclout Hill about a mile west-south-west of Patna. Among the Permian lavas of the Mauchline basin there are several flows which differ in texture only from certain members of the kylite suite of intrusions.

These facts leave little room for doubt that the kylite suite of Ayrshire is of Permian age. It follows from this that some of the faulting which affects the Coal Measures of Ayrshire is earlier than some of the Permian intrusions. It follows, too, that the kylite suite of intrusions can be used in the determination of the age of other intrusions associated with them.

[1] The Dundonald Hills in one-inch Sheet 22 are largely formed by a big sill of kylitic affinity.

[2] See p. 374.



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*Sub-Group 2a.* The chief mineralogical characters of this suite as a whole are the abundance of analcite, the prominence of brown barkevikitic hornblende in several members—notably camptonite and hornblende-picrite—and the serpentinisation of olivine where analcite is abundant. Sills of the teschenite suite are much less prominent in Central Ayrshire than those of the kylite suite. The main occurrences are at Glengyron, Lugar, Glaisnock, Carnivan Hill and Craigens. The Lugar and Glaisnock exposures probably belong to faulted parts of one sill. At Lugar this sill is banded and the difficult problem of its mode of differentiation and emplacement has been closely studied by Dr. Tyrrell (1917, pp. 84-131).

Sills of Sub-group 2*a* cut rocks ranging from sediments of the Upper Limestone Group to those of Coal Measure age. Rocks belonging to the suite are closely associated with picrite, olivine-biotite-dolerite of Sub-group 2c, and with quartz-bearing olivine-dolerite of Sub-group 3b, in the Craigens-Avisyard complex (Bailey and Simpson, 1926, p. 100 and figure) shown on the extreme east of Fig. 36. On Carskeoch Hill, south of Patna, Dr. Tyrrell has found a plug-like intrusion allied to bekinkinite, and closely resembling some varieties of the Lugar complex. It is intimately associated with an essexitic rock (Carskeoch essexite of Tyrrell) which is considered by the Survey to be very like parts of some of the nstrusions of Group 1, the Permian kylite suite (*Contrast* Tyrrell. 1912, p. 120; 1923, p. 256; 1928a, p. 284).

Further, in the Lugar sill, parts of the theralite layer, which overlies the central picrite, prove in thin section to be indistinguishable from certain types of rock found in kylite sills of Group 1. So here we have even stronger evidence than at Carskeoch for the genetic relationship between Group 1 and Sub-Group 2a.[1] Again, a vein very similar to some varieties of the lugarite veins of the Lugar sill, has been found cutting the Kilmein Hill kylite of Group 1.

From the above evidence, coupled with the decidedly alkaline (i.e. non-Tertiary) character of the rocks, it is thought that the sills of the teschenite suite (Sub-group 2a) are of Permian age, that the kylite and teschenite suites are intimately connected genetically, and that they do not belong to separate differentiation

[1] Dr. Tyrrell regards the Lugar theralite layer as a normal member of his Teschenite Series, and interprets the Carskeoch evidence in a different way (1917, p. 105; 1923, pp. 255-56).

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series. In the latter conclusion we are not in agreement with Dr. Tyrrell (*cf.* 1923, pp. 250-51.).

*Sub-Group 2b.* The ophitic alkali-dolerites, which often carry *fresh* olivine, are a very distinctive type. Important alkaline mineral characteristics are the presence of purple augite with green rims, accessory brown and green hornblende, and some biotite, alkali-felspar and analcite. All these characters are particularly pronounced in segregation veins, which consist largely of alkali-felspar, analcite and other zeolites. Such veins—'analcite-syenite' of Dr. Tyrrell (1912, p. 70)[1]—are well exposed at Howford Bridge, near Mauchline (not within Fig. 36).

A sill near Auchinleck House is a typical member of the group, and is probably continuous with the ophitic alkali-dolerite of Howford Bridge. The Troon sills and the thick sill extending from Prestwick to Auchincruive (the 'Auchincruive Whin')—none of which fall within Fig. 36—all closely resemble the Howford Bridge rock and are cut by veins similar to the 'analcite-syenite' of the Howford intrusion.

The sills of Sub-group 2b cut rocks ranging from Coal Measures to Permian lavas. The Auchincruive Whin is, however, apparently cut by a Permian ash neck which has been met with in the workings of a coal-pit about a mile east of Prestwick. A Permian date is therefore indicated by this field evidence. Moreover, the rocks themselves are more alkaline than the great majority of the West of Scotland Tertiary basalts, while in this respect they are easily comparable with the local Permian assemblage (lavas, kylite sills, etc.).[2]

*Sub-Group 2c.* A representative of this Sub-group is found only in the Craigens-Avisyard complex (Bailey and Simpson, 1926, p. 100 and figure) mentioned above, but it is of particular importance as a connecting link between the alkaline and sub-alkaline Permian intrusions. The outstanding features of this very ophitic olivine-dolerite are the conspicuous development of late-formed biotite plates and the absence of analcite. The rock occurs in *unchilled* contact with the Avisyard quartz-bearing dolerite, and may

[1] Since this paper was written Dr. Tyrrell has published a detailed account of occurrences of analcite-syenite in Central Ayrshire (1928b pp. 540-567).

[2] It must be understood that in the case of certain sills petrographically like those of Sub-group 2b, for instance that of the sill which *cuts sandstones above the Permian lavas* north-west of Mauchline, we cannot exclude the possibility of a Tertiary rather than a late Permian age (*Compare* Tyrrell, 1923, p. 259).

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therefore be regarded as of Permian age for reasons given below in connection with the latter intrusion.

*Sub-Group 3a.* The sills of this sub-group vary chiefly in the amount of decomposition they have undergone through the action of juvenile solutions. The augite is usually quite decomposed as well as the olivine, and the whole rock very highly serpentinised, even in specimens collected from bores. Occasionally, however, a relatively fresh sample can be obtained, and the rock is then seen to be a very ophitic and generally strikingly ophimottled dolerite with serpentinised olivine and much serpentinous material in the interspaces between the felspars. The serpentinous material probably in part replaces analcite, but fresh analcite has been seen in only one slide. The augite is pale brown to purplish, indicating a sub-alkaline character for the rocks. This feature is also brought out by the scarcity of analcite and biotite.

The main occurrences cut Coal Measures at Corbie Craigs (near Dunaskin Glen), Polnessan Burn (1 mile east of Polnessan), Rankinston, Auchingee Hill and Greengate Rig, and the tracing of these sills has brought out very clearly on the map the basin-shaped structure of the area in which they occur, the centre of the basin being occupied by the Kilmein Hill kylite sill at a higher horizon in the Coal Measures. Farther east dolerite similar to that at Corbie Craigs, etc., is exposed at Black Hill and Carsgailoch Hill.

The sills of Sub-group 3a cut Coal Measures. They have, however, been affected by all the faulting of these measures. Moreover, one of their number is pierced by a Permian neck at Burnhead cottage near Corbie Craigs; and two other examples of the same phenomenon are shown on the map near Waterside, and Polnessan Burn (1 mile north of Lethan Hill), though they are not so clearly established. Besides this, blocks of dolerite like the rocks of Sub-group 3a have been found in the agglomerate of the Permian neck at Houldsworth Colliery just east of Polnessan; and both at Corbie Craigs and Polnessan the sills are cut by sill-like and dyke-like intrusions of monchiquitic analcite-basalt of exactly the same type as is found so frequently in the Permian necks.

The Permian date of Sub-group 3a thus seems safely established. It also appears probable, from the evidence of the faulting, that the Corbie Craigs sills are earlier than the kylitic intrusions of Kilmein Hill, Craigmark Hill and Benbain (Group 1).

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The petrology of Sub-group 3a serves as a connecting link between that of Sub-group 2b and 2c on the one hand and 3b on the other. A segregation vein in the Polnessan Burn sill was found to be distinctly reminiscent of those occurring in the rocks of Sub-group 2b, for it contains alkali-felspar and a little biotite and hornblende.

*Sub-group 3b.* The sills of this Sub-group are closely related petrographically to those of Sub-group 3a, for the few moderately unaltered specimens collected are practically identical with the freshest examples of that Sub-group. The point of difference is that in Sub-group 3b, juvenile agencies have not only decomposed olivine and augite and produced much serpentinisation, but have also locally introduced quartz, sometimes as micropegmatite (*quartz de corrosion*), in all outcrops.

The chief occurrences lie in the Upper Limestone and Millstone Grit Series and crop out at Avisyard Hill (in the Craigens-Avisyard complex), Nith Lodge (Ashbeugh Glen), Dalmellington (Muck Burn), Dalnean Hill (with Dalcairnie Hill), and Grimmet Glen. Quartz has been noted at some place or another at all the localities mentioned. The exposures probably belong to a single sill which has been recognised again, with great likelihood, underground, in bores near Old Polquhairn. This correlation, considered as a whole, carries with it a recognition that the sill has been greatly faulted along with the Carboniferous strata into which it has been intruded.

The Avisyard sill, in the Avisyard-Craigens exposure, is accompanied by teschenite sills of Sub-group 2a, which occur both above and below and are chilled at the contacts. It is clear, therefore, that the Sub-group 3b must be earlier than Sub-group 2a and therefore either Carboniferous or Permian in date. The latter date is accepted because of the very close petrological similarity to Sub-group 3a, which, as we have seen, cuts Coal Measures and is therefore later than any known Scottish Carboniferous igneous activity.

It will be seen from the above account that while many of the Permian lavas and intrusions are more alkaline than any known Tertiary basalt lava of the Hebrides, some of the intrusions at any rate are distinctly sub-alkaline and chemically overlap the Tertiary range of composition. We do not propose to discuss at present Dr. Tyrrell's use of the rock-name 'crinanite' in connection with both Permian and Tertiary petrography in the Clyde

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region, but his use of the term certainly emphasises the point just mentioned.

A final point of interest may be touched on. The Permian or Permo-Carboniferous age of the Great Whin Sill or sills and of the big east and west dykes of the North of England and Central Scotland, is very generally accepted.[1]

These intrusions, however, are quartz-dolerites and they have long seemed rather out of place among the alkaline rocks of the Permian. Now that sub-alkaline dolerites of presumably Permian age are known which, in some cases, contain quartz introduced by juvenile agencies, the sub-alkalinity of the Whin Sill and east and west dykes no longer appears such an isolated phenomenon.

## V. Tertiary Period.

(*a*) *Dykes.*

Basic dykes of post-lower Old Red Sandstone age, cutting rocks of all ages up to and including the New Red Sandstone, are common in Central Ayrshire. A preliminary examination of a large number of them shows that, from their petrographical affinities, they are probably mostly of Tertiary age. These latter fell into two classes,

(i) tholeiites,

(ii) olivine-dolerites near to the crinanite type.

In the case of the former, the more abundant type, the majority run in either a north-west or north-north-west direction; while those of class (ii) commonly run from east to west or west-north-west.

(*b*) *Sills.*[2]

A few small sills of olivine-dolerite occur, to which, on petrographical grounds, a Tertiary age may be assigned. One example, which cuts Productive Coal Measures, is exposed below the New Bridge at Ayr.

[1] Dr. Tyrrell (1923, p. 258), has recently expressed doubts about this. *See also* E. B. Bailey in 'The Geology of the Glasgow District,' (*Mem. Geol. Surv. Scotland*), 2nd. (Revised) Edition, 1925, pp. 149-152; and D. Balsillie, 'Contemporaneous Volcanic Activity in East Fife; *Geol. Mag.*, LXIV, 1927, pp. 492-493.

[2] *See also* footnote, p. 379.

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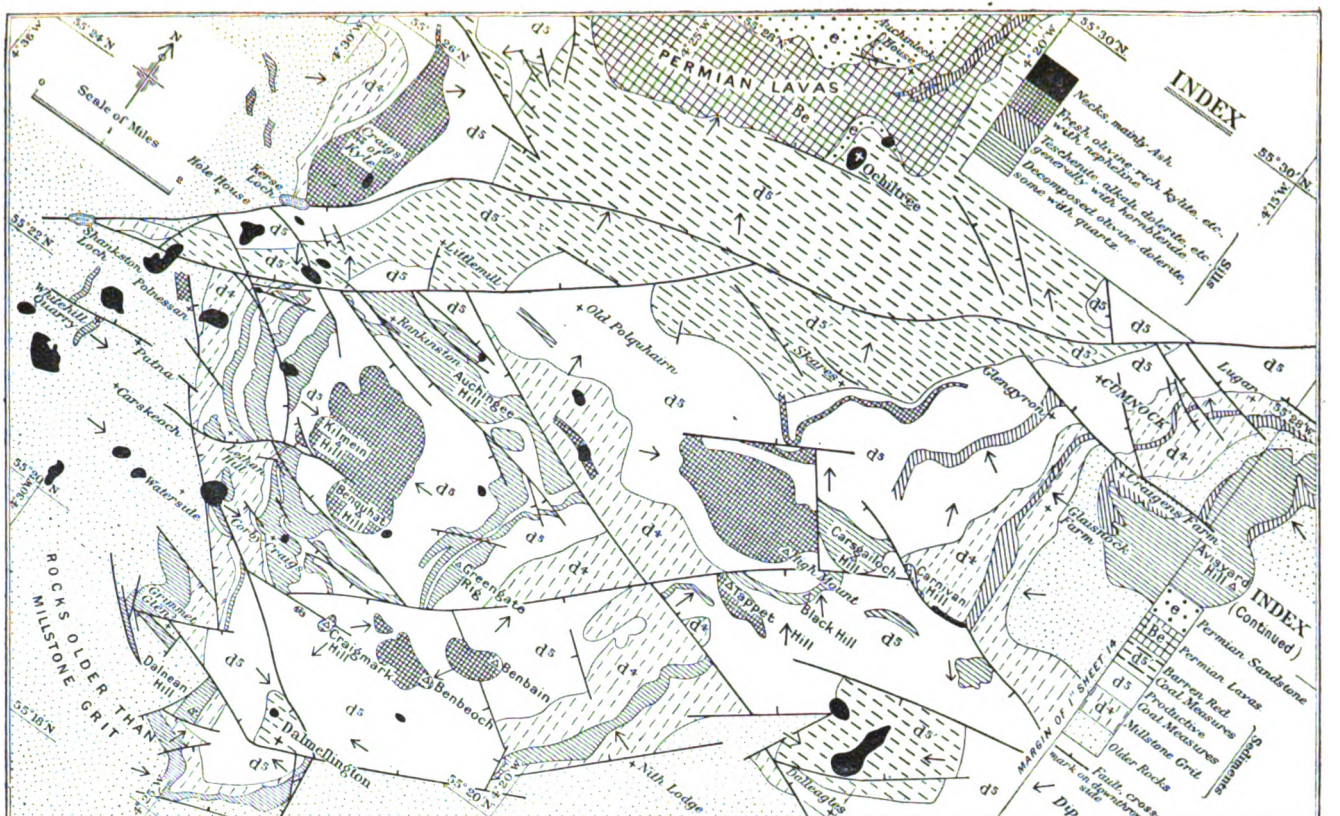


Fig. 36.—Map of sills and necks, Patna, Cumnock and Dalmellington.

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## ANALYSES[1]—CENTRAL AYRSHIRE.

| | I | II | III | IV | V | VI | VII | |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ .. | 58.88 | 22.03 | 28.12 | 35.71 | 39.35 | 45.62 | 45.70 | $SiO_2$ |
| $Al_2O_3$ .. | 15.86 | 22.91 | 25.85 | 29.62 | 11.60 | 14.18 | 12.32 | $Al_2O_3$ |
| $Fe_2O_3$ .. | 2.49 | 0.46 | 7.21 | 4.63 | 9.31 | 2.95 | 0.99 | $Fe_2O_3$ |
| FeO .. | 3.46 | 36.68 | 17.96 | 7.42 | 4.76 | 8.40 | 9.64 | FeO |
| MgO .. | 4.40 | 1.91 | 1.34 | 1.04 | 10.58 | 9.69 | 12.45 | MgO |
| CaO .. | 5.75 | 0.07 | 0.30 | 0.24 | 10.55 | 9.25 | 10.12 | CaO |
| $Na_2O$ | 2.70 | 0.08 | 0.10 | 0.03 | 3.06 | 3.61 | 2.74 | $Na_2O$ |
| $K_2O$ .. | 2.02 | 0.03 | 0.03 | 0.07 | 0.86 | 1.48 | 1.64 | $K_2O$ |
| $H_2O > 105°$ . | 0.65 | 10.65 | 9.84 | 12.25 | 3.76 | 2.29 | 2.12 | $H_2O > 105°$ |
| $H_2O < 105°$ . | 1.74 | 0.63 | 0.88 | 1.80 | 1.44 | 0.27 | 0.16 | $H_2O < 105°$ |
| $TiO_2$ .. | 1.17 | 3.63 | 3.05 | 6.25 | 3.38 | 1.61 | 1.50 | $TiO_2$ |
| $P_2O_5$ .. | 0.22 | 0.18 | 0.22 | 0.02 | 0.82 | 0.47 | 0.33 | $P_2O_5$ |
| MnO .. | 0.52 | 0.04 | 0.22 | 0.04 | 0.79 | 0.32 | 0.29 | MnO |
| $CO_2$.. .. | 0.09 | 0.40 | 3.92 | tr. | 0.19 | 0.05 | 0.07 | $CO_2$ |
| $SO_3$.. .. | —— | 0.27 | 0.24 | 0.22 | —— | —— | —— | $SO_3$ |
| Cl .. .. | tr. | —— | —— | —— | 0.05 | 0.03 | 0.01 | Cl |
| $FeS_2$ .. | nt. fd. | —— | —— | —— | 0.03 | nt. fd. | nt. fd. | $FeS_2$ |
| $Cr_2O_3$ .. | —— | 0.05 | 0.04 | 0.07 | —— | —— | —— | $Cr_2O_3$ |
| (Co,Ni)O .. | 0.03 | nt. fd. | nt. fd. | nt. fd. | 0.03 | 0.03 | 0.02 | (Co,Ni)O |
| BaO .. | 0.04 | —— | —— | —— | 0.01 | 0.02 | 0.03 | BaO |
| $Li_2O$ .. | tr. | tr. | tr. | tr. | tr. | nt. fd. | tr. | $Li_2O$ |
| Org. Mat. .. | —— | 0.03 | 0.57 | 0.73 | —— | —— | —— | Org. Mat. |
| Less O for Cl | | | | | 0.01 | 0.01 | | Less O fr. Cl |
| | 100.02 | 100.05 | 99.89 | 100.14 | 100.56 | 100.26 | 100.13 | |

nt. fd.=not found. tr.=trace. Org. Mat.=Organic Matter.

I. (25255,[2] Lab. No. 840). Old Red Sandstone lava. Near shore, 540 yards N.W. by W. of Dunure Station. Hypersthene-andesite (felspar and augite fresh, hypersthene partly fresh). Anal. E. G. Radley.

II, III, and IV. (22084, 22086, 22088 and Lab. Nos. 754, 755, 756 respectively). Millstone Grit detrital volcanic rocks. In bank of small stream 300 yards W.24°N. of Gateside farm, 2 miles E. of Ayr. Much altered volcanic detritus. Anal. B. E. Dixon.

V. (25241, Lab. No. 837). Permian lava. Quarry 450 yards E. 5° N. of Grassmilees, and ¼ mile S.E. of Mauchline. Nepheline-basalt (nepheline partly fresh, olivine decomposed). Anal. E. G. Radley.

[1] Analyses I, V, VI, and VII have appeared in 'Summary of Progress for 1927, Part I' (*Mem. Geol. Surv.*), 1928, p. 80.

[2] No. of rock slice in Scottish Collection of H.M. Geological Survey.

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VI. (25246, Lab. No. 838). Permian lava. East end of railway cutting, Tarbolton station. Olivine-basalt (olivine fresh, ? nepheline pseudomorphs). Anal. E. G. Radley.

VII. (25252, Lab. No. 839). Permian sill. Quarry, Craigs of Kyle 1½ miles W.N.W. of Rankinston Station. Alkaline olivine-dolerite of kylite suite (olivine fresh, nepheline mostly decomposed). Anal. E. G. Radley.

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*Maps.*

*Quarter inch to mile Geological Survey (colour-printed).*

Sheet 16. Includes Ayrshire (southern half): 1904.

Sheet 14. Includes North Ayrshire: in preparation.

*One inch to mile Geological Survey (hand-coloured).*

Sheet 8. Includes Ayrshire (south-eastern part): 1893. A revised colour-printed edition is in preparation.

Sheet 13. Includes Ayrshire (part of coastline at Turnberry): revised edition 1902.

Sheet 14. Ayrshire (central and south): 1868.

Sheet 15. Includes Ayrshire (south-east part): 1870.

*One inch to one mile Geological Survey (colour-printed).*

Sheet 22. Includes Ayrshire (north part): 1928. Two editions are published, showing solid and drift geology respectively.

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(Only the more important references are given. The dates are those of publication of volume quoted. The date at which a paper was read, if prior to that of publication, is shown in square brackets).

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1927. Eyles, V. A., and A. G. MacGregor, in 'Summary of Progress for 1926' (*Mem. Geol. Surv.*), p. 58.

ADDENDA.

*Published since preparation of this paper.*

1928a. Tyrrell, G. W., 'A Further Contribution to the Petrography of the Late-Palaeozoic Igneous Suite of the West of Scotland,' *Trans. Geol. Soc. Glasgow*, XVIII, pp. 259-294.

1928b. Tyrrell, G. W., 'On some Dolerite-Sills containing Analcite-Syenite in Central Ayrshire,' Q.J.G.S., LXXXIV, pp. 540-567.

1928c. Eyles, V. A., and A. G. MacGregor, in 'Summary of Progress for 1927, Part I' (*Mem. Geol. Surv.*), p. 58.

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## CLASSIFICATION TABLE. PERMIAN SILLS.

| | | Rock Groups and Types. (Types within each sub-group are frequently found in close association). | Corresponding Rock Names used by Dr. Tyrrell. |
|---|---|---|---|
| Group 1 | | Fresh olivine-rich kylite, etc. with nepheline. (' Kylite suite ') (These rocks are characteristically fresh and unweathered in the field and in thin section). Types include essexite, olivine-rich doleritic theralite, picrite. (A vein closely resembles some varieties of lugarite). | Kylite and allied types, essexite (Crawfordjohn type) and essexite (Carskeoch type). These form part of Tyrrell's Crinanite Series. |
| Group 2 | | Teschenite, alkali-dolerite, etc., generally with hornblende. (These rocks often weather deeply in the field, but generally provide fresh material for thin sections). | |
| | a | Teschenite, hornblende-, and nepheline-teschenite, doleritic theralite (sometimes with hornblende), camptonite, hornblende-picrite, peridotite. (' Teschenite suite ') (With lugarite as a vein). | Teschenite, nepheline-teschenite, theralite (Bellow type), picrite-teschenite (Lugar type), bekinkinite, peridotite and lugarite. These form Tyrrell's Teschenite Series. |
| | b | Ophitic alkali-dolerite. (With analcite-syenite as veins). | Alkali-dolerite (in part), crinanite (in part) and analcite-syenite. These form part of Tyrrell's Crinanite Series. |
| | c | Ophitic olivine-dolerite with biotite. (Craigens-Avisyard sill-complex only). | |
| Group 3 | | Decomposed olivine-dolerite, sometimes with quartz. (These rocks are characteristically deeply weathered in the field, probably because of previous juvenile decomposition which has no relation to the present surface. Fresh olivine and augite rarely survive). | |
| | a | Ophimottled olivine-dolerite, usually decomposed. (With an alkali-felspar vein). | Alkali-dolerite (in part) of Tyrrell's Crinanite Series. |
| | b | Decomposed olivine-dolerite with juvenile quartz. (Veins and patches with intergrown alkali-felspar and quartz are characteristic of Dalmellington exposures). | Most of occurrences classed by Tyrrell, in 1912, under general title ' alkali- and essexite-dolerites,' but the presence of quartz was not recorded, except in veins at Dalmellington. |

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# No. XV.—Dykes and Associated Intrusions of the Island of Bute.

By H. J. W. Brown, M.Sc., Ph.D., A.K.C.

(Read 8th November, 1928; issued December 7th, 1929).

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## I.—Introduction.

The Island of Bute is divided into approximately equal halves by the Highland Boundary Fault which crosses the island from Rothesay Bay to Scalpsie Point. The northern hilly portion consists of Highland schists, phyllites and grits. South of the Boundary Fault most of the ground is occupied by the conglomerates and sandstones of Old Red Sandstone Age which form a featureless tract of country. The general dip of these sediments is to the South-West and at Ambrisbeg, Scalpsie Bay, and Kilchattan they are overlain by rocks of Lower Carboniferous Age. At Kingarth and St. Colmac raised beaches cross the island and they also occur at several localities around the coast. South of Kingarth, the country is very rugged and is

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composed mainly of igneous rocks. The southern portion of the island is cut into blocks by a series of faults of Tertiary Age trending N.W. to S.E. and N.E. to S.W. Numerous dykes penetrate the sediments and lavas alike and it is the purport of this paper to describe these dykes and certain associated intrusions.

*Previous Literature.* MacCulloch (1) mentioned that numerous trap-veins occur in Bute and referred to the group of dykes on the Kilchattan Bay foreshore and the E.–W. dyke at Ascog.

Bryce (2) described the dykes of Bute as composed of greenstone and basalt and stated " they traverse the strata in various directions and in some cases can be traced for several miles continuously preserving nearly the same width and direction throughout . . . . . A narrow dyke branches off in several filaments which unite again and portions of the rock are often found entangled in the dyke." He refers also to the E.–W. dyke at Bogany Point

W. Gunn mapped the geology of the island on the six-inch scale, but no Geological Survey Memoir on the island has been written, although references to the geology of the South of the island appear in a Geological Survey Memoir (3).

Dr. W. R. Smellie (4) has written two papers on the igneous geology of the South of the island and dealt fully with the lava flows and a Tertiary composite sill. Dr. G. W. Tyrrell (5) has made one or two references to the Bute dykes, based upon an examination of Dr. Smellie's material. The object of the present paper is to continue and amplify the work of the last two authors as far as it relates to these dykes and certain associated intrusions.

1. MacCulloch, J. ' The Geology of the Western Islands of Scotland,' ii, 1819.
2. Bryce, J. ' The Geology of Arran and other Clyde Islands,' 1872.
3. ' Geology of N. Arran, S. Bute,' *Mem. Geol. Surv.*, 1903.
4. Smellie, W. R. ' The Tertiary Composite Sill of S. Bute.' *Trans. Geol. Soc. Glasgow*, XV, 2, 1915, p. 121.

4a. Smellie, W. R. ' The Igneous Rocks of Bute,' *Trans. Geol. Soc., Glasgow*, XV, 1916, p. 334.

5. Tyrrell, G. W. ' Tertiary dykes of the Clyde Area,' *Geol. Mag.*, 1917, p. 305.

In the metamorphic rocks on the North of the island the dykes are relatively few in number and have a general N.N.W.–S.S.E. direction, which becomes N.W.–S.E. West of Loch Fad. Two dykes cross the centre of the island in an E.–W. direction, and a third E.–W. dyke exposed on the foreshore at Craigmore

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is probably a continuation of the more northerly of these. In the Old Red Sandstone and igneous rocks, the dykes become more numerous and generally trend N.–S. or N.E.–S.W., although some of the longer dykes belonging to the former group commence in a N.N.W.–S.S.E. direction and change abruptly to N.N.E.–S.S.W., and individual dykes belonging to the latter group may vary in direction from E.N.E.–W.S.W. to N.N.E.–S.S.W.

The dykes vary in thickness from a foot or two to about 100 feet, but the average thickness is about 5 feet. The wide dykes form either wall-like features or scarps. The narrow dykes do not build features, and tend to hade in conformity with the bedding planes of the country rock. Some of the longer dykes can be traced for a mile or two, but many of them are small and have only a short extension above ground. It is only in a few cases where the dykes are seen to die out along the foreshore that their length can be determined. Jointing has affected most of the dykes, frequently producing a columnar structure and spheroidal weathering. Towards the centre of the large dykes, the joints fail, but there is sometimes developed a medial vesicular zone in which the vesicles sometimes become filled with quartz or calcite.

In the thin dykes a plane of weakness tends to develop in their central portions, and in the thicker dykes two such planes of weakness may develop in their marginal portions within a foot or two of their planes of contact with the country rock. Fissures may subsequently develop along these planes of weakness and provide a channel for the intrusion of a further quantity of magma, ultimately producing triple or quintuple intrusions. The plane of weakness may be detected in the field by the belts of xenolithic material that occur along them. Several of the dykes in Bute show evidence of having been emplaced by two or more intrusions in rapid succession in this manner.

Metamorphism of the country rock by the dykes is not a conspicuous feature. In the older rocks north of the Boundary Fault it is absent, and in the younger rocks it is limited to a bleaching and indurating of the sandstone, for a few inches on either side of the dyke.

The dykes of Bute can be assigned to four periods of igneous activity: Devonian, Carboniferous, Permo-Carboniferous and Tertiary.

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## II.—Dyke of Devonian Age.

A narrow dyke of mica-lamprophyre at the N.E. corner of the Bull Loch is the solitary representative in Bute of a large group of dykes of Devonian Age found in Argyllshire.

It has a high hade to the N.W. and forms a small feature on the hill side which can be traced in a N.E. direction for about a quarter of a mile.

In the hand specimen the rock is compact, fine-grained, reddish-grey in colour.

Under the microscope it is seen to consist essentially of crystals of biotite, felspar, and iron-ore.

The felspar occupies approximately half the slide and occurs in laths about five times as long as broad with a sheaf-like arrangement. Some of the felspar is without crystal form, and is then always more turbid than the idiomorphic varieties, and is frequently sprinkled with globulites of iron-ore.

Much of the felspar is untwinned, and is considered to be orthoclase, but twinned varieties occur and appear to be an acid plagioclase. The plagioclase is slightly in excess of the orthoclase, so the rock falls into the kersantite group of Rosenbusch.

A small quantity of quartz, clouded with inclusions, occurs and is the latest mineral to crystallise. The most conspicuous constituent of the rock is a strongly pleochroic biotite, which occurs in small elongated rectangles with ragged edges and as hexagonal flakes. It is almost as prevalent as the felspar. The crystals are commonly bleached in the interior and retain the deep brown colour only at the margins. Less frequently the bleaching has commenced from the exterior, and a core of dark brown biotite remains. Some of the biotite has suffered chloritisation, and in some cases is completely pseudomorphed in chlorite.

Augite occurs in colourless grains, but is less abundant than the biotite. Hornblende is very rare. It is brown in colour and shows the characteristic crystal form. Apatite in long needles is an abundant accessory. Iron-ore is scattered uniformly throughout the slide. It usually clings to the biotite and sometimes is enclosed by it. It possesses the magnetite habit. A few small ovoid vesicles filled with calcite occur. The structure of the rock is non-porphyritic, and shows the tendency to panidiomorphism usually associated with this group of rocks.

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### III.—Dykes of Carboniferous Age.

Dykes of Carboniferous age are very numerous in the Old Red Sandstone and Carboniferous rocks south of the Boundary Fault, but do not penetrate the older rocks of the north of the island.

Apart from a few solitary dykes they occur in groups in three localities.

1. Between Kerrycroy and Kilchattan Bay on the foreshore, becoming very numerous between Bruchag and Kerrytonlia Points.

These dykes are intruded into the Old Red Sandstone and have a general E.N.E. trend, but at Kerrytonlia on the north side of the road a few yards west of Kerrytonlia Farm there is a quarry, exposing a 6 ft. dyke trending in a N.–S. direction.

They range in thickness from 2 to 12 ft., but the wider dykes are multiple intrusions consisting of three sheets separated by belts of xenolithic material. Petrographically they are basalts of the Markle and Markle-Dunsapie types, but in the Mount Stuart Policies, south of the boat house a 6 ft. dyke of mugearitic basalt occurs.

2. At Stravannan Bay, on the foreshore three 4 ft. dykes of Markle basalt occur intruded into the Old Red Sandstone. One has a north to south direction and the other two trend E.N.E.
3. South of Hawk's Nib Point, on the raised beach a group of thin irregular and impersistent dykes of much altered olivine basalt occur. They are so altered, the junction between the sediment and dykes become difficult to determine.

Three solitary dykes occur.

1. A few yards south of Kilchattan Pier on the foreshore, a 5 ft. dyke of mugearitic basalt is intruded into the Old Red Sandstone conglomerate in an E.N.E. direction.
2. South-west of Barr Hill, on the foreshore, a 3 ft. dyke of mugearite is intruded into a small neck of agglomerate in an E.N.E. direction.
3. A few yards north of Crag A Mhara, on the foreshore, a 3 ft. Markle basalt dyke is intruded into the cornstones in a N.E. direction.

In the hand specimen from the dykes, the Markle basalts vary in colour from dark blue with clear felspar phenocrysts

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to light grey with white opaque macro-phenocrysts of felspar. Pinkish coloured varieties occur on the Stravannan Bay foreshore and at the Kerrytonlia road quarry.

The hand specimen from the mugearites are reddish-coloured and fine-grained, but the fissile structure usually associated with rocks of this group is rarely seen in the dykes.

*Petrography—Markle.* In their sections the Markle basalts are seen to consist of large felspar phenocrysts, set in a ground mass of felspar laths, and granules with varying amounts of iron-ore and tiny grains of augite or its decomposition products. A dark glassy base highly charged with felspar microlites is present in some varieties. Augite phenocrysts sometimes occur and become sufficiently numerous in some types to warrant the name Markle-Dunsapie.

The felspar phenocrysts usually show good crystal form but misshapen plates occur. Twinning according to the Carlsbad and Albite laws is common, and that according to the Pericline law is by no means a rarity. Symmetrically cut sections of felspar phenocrysts showing carlsbad twinning give an extinction angle up to 34° indicating a felspar of labradorite-bytownite composition ($Ab_2$ $An_8$). Zoning is common, and is especially well seen in sections parallel to the clinopinacoid (010). Tiny grains of augite or its alteration product and little rods of magnetite arranged along the cleavage planes are common inclusions of the felspar phenocrysts. In some of the felspar phenocrysts wisps of white mica have developed as an alteration product. The felspar of the ground mass is usually in the form of simply-twinned laths, a fair proportion of which are orthoclase sometimes trachytically arranged.

Augite occurs in colourless or pale yellow-brown granules but is rarely seen fresh: more frequently it is represented by chlorite or ferruginous matter. In the Markle-Dunsapie type it has a purplish tinge, and shows good crystal form. Magnetite occurs in small and imperfect octahedra scattered throughout the slide. Ilmenite partially altered to leucoxene is seen in some slides.

Albitisation of the felspars in the manner described by Grabham and Bailey (*Geol. Mag.*, 1909, p. 250) is a very common change in dykes of the Markle type, and few have escaped entirely. Most commonly it has affected the phenocrysts only, but in some cases the alteration has extended to the felspars of the ground



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mass. Not infrequently the felspar phenocrysts are entirely altered to pseudomorphs of calcite, while little laths of the ground mass remain perfectly fresh.

In the more weathered varieties, the calcite pseudomorphs have suffered haematisation. This change may affect the centre of the pseudomorph, first producing a core of haematite or alternatively it may proceed from the periphery of the crystal toward the interior, and a fringe of haematite will border the crystal and line its cleavage cracks.

The most weathered varieties show pseudomorphs of calcite partially altered to haematite set in a ground mass of tiny grains of iron, much diffused chloritic matter and granules of calcite. Olivine never occurs fresh, but serpentinous matter is diffused throughout the slide, and may sometimes represent augite.

*Mugearites.* The mugearite dykes are very decomposed and yield unsatisfactory sections. They consist essentially of little felspar laths and tiny cubes and grains of magnetite set in a dark-coloured matrix. Little patches of a green decomposition product are sometimes seen in the matrix and appear to be chlorite, but most of the matrix is clouded and stained with ferruginous decomposition products. The felspar laths are usually very turbid with decomposition products, but some are fresh and are then seen to be simply twinned and give straight extinction. A few small patches of calcite occur, but the mineral they represent is not evident.

## IV.—Dykes of Permo-Carboniferous Age.

Two wide and persistent quartz-dolerite dykes of Permo-Carboniferous age cross the island in an E.-W. direction, but neither of them forms a prominent feature in the landscape for a long distance.

The more southerly and wider dyke crosses the island from a point half-a-mile south of Ettrick Bay to Ascog Point. Between Ettrick Bay and St. Ninian's Bay it is well exposed on the foreshore and hades at high angle to the south, in conformity with the dip of the beds in the metamorphic rocks of this part of the island. At Upper Ardroscadale on the west side of the road leading from Ettrick Bay to St. Ninian's Bay, it is poorly exposed in an overgrown pit, and on the east side of the road leading from Barone to Scalpsie Bay there is another poor exposure. At Cnoc na-h-ulaidhe, N.W. of Loch Fad, it builds the small feature and is

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well exposed in the banks of the stream flowing to the north of that eminence. At the northern end of Loch Fad it is again exposed and unaffected by the boundary fault; it can be traced westward by the slight elevation of the ground until it cuts the Carboniferous lavas of the Ascog Plateau, but no sections are visible. On the foreshore at Ascog Point it is well exposed and is truncated by the fault that bounds the northern edge of the Ascog Plateau. At Ardlamont Point on the mainland to the west, a similar wide E.–W. dyke occurs in alignment with this dyke, and is probably a continuation of it.

The more northerly dyke crosses the island from Ettrick Bay to Rothesay Bay. About a quarter of a mile south of Ettrick Bay on the east side of the road leading from Ettrick Bay to St. Ninian's Bay, the rock is worked and the quarry exposes the dyke and its contacts with the country rock. The dyke hades at 30° to the south, and passing from the south to the north side of the quarry the section shows

(*a*) 2 ft. fine-grained rock separated by a major joint-plane from

(*b*) 9 ft. coarser-grained massive rock separated by a joint-plane lined with crystals of calcite from

(*c*) 12 ft. coarser-grained rock passing into

(*d*) a few feet brownish-red rock with spheroidal weathering

(*b*) and (*c*) are penetrated by anastomising veins of pink rock up to ½ in. thickness. The contacts with the phyllites are very irregular.

At Rothesay the rock is again worked, and the section shows the dyke 30 ft. wide, hading 30° to the south with well developed joints and a tendency to columnar structure.

On the foreshore of the western horn of Rothesay Bay, opposite the Glenburn Hydro, a third E.–W. dyke occurs and may be traced to Bogany Point. It is apparently a continuation of the more northerly dyke displaced by the Boundary Fault.

In the hand-specimens from the central portion of the dyke it is a coarse-grained, grey-coloured phaneric rock. Towards the margin of the dyke it becomes darker in colour and finer grained. The slightly weathered surface exhibits a pinkish tinge, and in the extreme stage of weathering the rock breaks down into a reddish-brown earth. Thin pink veins of a more acid material occur and are well seen in the Ettrick Bay Quarry.

In thin sections the rock consists of an aggregate of crystals

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of felspar, iron-ore, pyroxene, and a little micropegmatite. The felspar occurs as broad laths, and when fresh shows albite and carlsbad twinning. The crystals are usually zoned and in symmetrically cut sections their extinction angles indicate a range in composition from a labradorite kernel to oligoclase border. Some untwinned crystals occur and probably represent orthoclase. More generally the felspars are much decomposed and the basic cores of the felspars are represented by calcite, while the more acid felspars undergo kaolinisation.

Micropegmatite fills the spaces between the felspar and in coarser grained varieties forms a mesostasis, but it is usually small in amount. In the finer grained rocks it shows the pseudospherulitic structure giving the characteristic black cross between crossed nicols. In the more decomposed sections the micropegmatite is represented by chlorite, calcite, and secondary quartz. In sections cut from the marginal portions of the dyke, little patches of brown glass occur.

The augite is invariably colourless and occurs in two forms, long narrow blades elongated along the " C " axis and in planes sometimes idiomorphic but more usually ophitic towards the felspar. A sahlite structure occurs in some of the crystals, especially those that exhibit a columnar habit, but the lamination is generally restricted to the central portion of the crystal. Twinning on the orthopinacoid is very common, and is frequently repeated, and when combined with the basal lamination it produces a herring-bone structure. Decomposition of the augite frequently commences along the planes of the basal striation by the separation of calcite granules. These frequently fill the interior of the crystal and impart to it a dusky appearance.

A more common type of alteration of the augite is the paramorphic change to uralite. The change usually commences from the periphery of the crystal, but there is no well-defined boundary between the amphibole and pyroxene. In some of the more weathered sections the augite is completely replaced by this mineral which sometimes shows a radial structure. Associated with this change is the production of a highly pleochroic biotite. Chlorite sometimes pseudomorphs the augite and can be distinguished from the uralite by its lower polarisation colours. The final product of the alteration of the augite is a pale green serpentine with little grains of magnetite.

Hypersthene occurs somewhat sporadically, associated, but

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not intergrown with the augite. It has the characteristic pleochroism, and is fringed with a green fibrous mineral.

Primary brown hornblende occurred in one slide in small prismatic crystals associated with the felspar. Apatite in long narrow needles occurs fairly abundantly, and tends to be associated with the micropegmatite. The iron-ore is ilmenite and forms a large open network. It is moulded on to the augite and frequently shows weathering to leucoxene.

*Aplite Veins*:—These are much finer grained than the rest of the rock, and consist essentially of quartz, felspar, and iron-ore lying in a matrix of turbid brown material. The quartz occurs in small irregular grains, and, with the felspar, composes the bulk of the rock. The felspars are kaolinised and many are untwinned. These are presumably orthoclase, but the twinned varieties can be identified as oligoclase. The iron-ore occurs in abundant, but tiny granules and little rods scattered throughout the quartz-felspathic material. The ferro-magnesian constituent is very rare, and is represented by pseudomorphs of calcite and chlorite. Calcite and chlorite also occur in tiny veins throughout the slide. The turbid brown matrix probably represents a fine micro-pegmatite for in some areas in the slide a pseudo-spherulitic structure is seen producing a dark sector, which sweeps round the aggregate as the stage is rotated. The junction of the vein with the rest of the rock is sharp, and there is no chilled margin.

## V.—Intrusions of Tertiary Age.

The intrusions of Tertiary Age in Bute, include a large sill that extends in a south-easterly direction across the south of the island from a point 500 yards south of Hawk's Nib to Garroch Head, several small intrusions and a large number of dykes. A second sill of Tertiary Age which crosses the south end of the island and truncates the former sill is a composite intrusion. It consists of a core of hypersthene-dolerite flanked by two sheets of quartz-porphyry, each of which has a marginal sheet of dolerite in contact with the country rock. It has been fully described by Dr. Smellie, and will not be dealt with in this paper.

The dykes are scattered throughout the island. In the north of the island they are rare in the west, but become more numerous towards the north-east where they are exposed on the eastern slopes of Kames Hill, Lyeing Hill, and the North Hill of Bullochreg, while several dykes radiate from the Bull Loch.

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In the Old Red Sandstone they are again numerous and are exposed in the quarries and on the foreshore at Stravannan Bay, Ascog, and Kilchattan. At White Port, south of Kilchattan, a large number of thin dykes are found intruded into the sandstones of the foreshore, and a few dykes cut the lavas and agglomerates of Carboniferous age.

In the metamorphic rocks of the north of the island, the dykes tend to follow a N.N.W. direction, becoming more north-westerly west of Loch Fad; although an E.–W. dyke occurs at the Bull Loch. In the Old Red Sandstone the direction of the dykes is mainly N.–S., but some of the longer dykes commence in a N.N.W. direction and then turn abruptly S.S.W. At Kilchattan they frequently have a north-easterly direction parallel to those of Carboniferous age.

The Tertiary dykes are usually wider than those of Carboniferous age and may attain a width of 40 ft., although to the west of the island the wide dykes are frequently multiple intrusions. In Glen More they become wide enough to give rise to scarp and terrace structure on a small scale.

Multiple dykes occur at Ettrick Bay and Stravannan Bay. The Ettrick Bay dyke is well-exposed at the north end of the Bay on the foreshore, and can be traced for a distance of two miles along the western side of Glen More. It has a high hade to the east and is a triple intrusion. Its central member is 14 ft. wide and the marginal members each about 2 ft. wide. All the components have a tachylytic margin, and between the central and marginal portions of the intrusion are enclosed fragments of phyllites. A second triple dyke occurs on the raised beach about a mile south of Ettrick Bay, and can be traced to St. Ninian's Bay. Its central member is about 30 ft. wide, and the eastern and western marginal members, 2 ft. and 4 ft. wide respectively. Between the central and eastern portions of the dyke are included large lenticles of schist, measuring 2 to 3 ft. in length. Like the previous dyke all its component intrusions have tachylytic selvages, and the eastermost intrusion passes into a tachylytic dyke before it finally disappears beneath the shingle of the foreshore.

A third triple dyke is the most southerly dyke on the Stravannan Bay foreshore. Its central intrusion is 4 ft. wide, and the marginal members each about 2 ft. wide. At the northern end of the dyke

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all the component intrusions pass into tachylyte dykelets which peter out on the sandstones of the foreshore.

*Petrography.* With the exception of the composite sill, the intrusions of Tertiary Age in Bute can be referred to two distinct and contrasted rock-types, namely: tholeiites and crinanites. The tholeiites comprise the vast majority of the dykes occurring in the island and one or two small sills. The crinanites are much more localised in their distribution, and include the large sill and one or two associated dykes. In the field the tholeiites can frequently be distinguished by their tachylytic margins, a feature not exhibited by the crinanites.

*Note on the Usage of the Term Tholeiite.* The term tholeiite was introduced by Steininger for basalts possessing intersertal texture. Rosenbusch used the term for both porphyritic and non-porphyritic olivine-free or olivine-poor plagioclase augite rocks with intersertal texture. The Geological Survey Petrographers in their classification of the Mull Rocks restricted the usage of the term to non-porphyritic rocks of similar composition with intersertal texture. Rocks containing a definite and continuous ground-mass constitute the augite-andesites. Dr. G. W. Tyrrell in summarising the characters of the Arran tholeiite dykes[1] admitted both porphyritic and non-porphyritic varieties and widened the connotation of the term to include holocrystalline rocks with intergranular texture. More recently the same author has defined the tholeiites as oversaturated basalts rich in lime in which highly calcic plagioclase felspars appear mostly as phenocrysts.[2]

The tholeiites are medium to fine-grained rocks dark-grey or bluish-grey in colour with Sp. Gr. varying from 2.7–2.91.

Several varieties have been described by various authors, and in the following description they are treated under the headings:

i. Brunton type of tholeiite.
ii. Olivine tholeiites of the Brunton type.
iii. Salen type of tholeiite.
iv. Corrie type of tholeiite.
v. Largs type of tholeiite.
vi. Cumbrae type of tholeiite (Cumbraite).
vii. Quartz-dolerites.

[1] Excursion to Arran. *Proc. Geol. Assoc.*, XXXV, 1924, p. 406.
[2] 'The Principles of Petrology,' 1926, p. 129.

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(i) *Brunton type of tholeiite.* The Brunton dyke, Bingfield, Northumberland, figured by Harker[1] and figured and described by Teall,[2] is the rock on which the type is based.

Its microscopical characters are described as "long narrow lath-shaped felspars, irregular crystalline grains and plates of nearly colourless pyroxene, and a small quantity of nearly opaque interstitial matter."

Several dykes conforming to the Brunton type, but exhibiting minor variations in the quantitative relations of their constituents occur in Bute.

An easily accessible dyke of this type with a diminished quantity of glassy base is a 20 ft. N. to S. dyke between Ascog and Kerrycroy on the foreshore. It has caught up fragments of Old Red Sandstone in its intrusion and xenoliths of quartz occur in its marginal portions.

In these sections the rock is seen to consist of a few slightly corroded microphenocrysts of felspar set in a plexus of augite granules and felspar laths with a subordinate amount of iron-ore and in interstitial glassy base. The felspar microphenocrysts are in the form of laths and square-shaped sections twinned on the albite and carlsbad laws and frequently showing slight zonary banding. They consist of a basic labradorite.[4] Inclusions of pyroxene and iron-ore are common and have a noticeable tendency to be arranged along definite planes within the crystal.

In the ground mass, the felspar laths are usually much elongated with bifid and trifid terminations and are frequently curved and fractured through intercrystal pressure at a late stage in the consolidation of the magma, and have a composition of $Ab_1$ $An_1$. Stellate groupings of the felspar laths due to crystallisation from several common initial points is a characteristic feature of this rock.

[1] A. Harker, 'Petrology for Students,' 3rd Edition, 1902, p. 193.

[2] J. J. H. Teall, 'Petrological Notes on some North of England Dykes,' *Q.J.G.S.*, XL, 1884, pp. 236-7.

[3] A. Holmes and H. F. Harwood, 'The Age and Composition of the Whin Sill and the related Dikes of the North of England.' *Min. Mag.*, XXI, 1928., p. 520.

[4] Although none of the Bute Brunton tholeiites contains glomero-porphyritic aggregates of anorthite crystals, the occurrence of microphenocrysts of a basic felspar is a common feature of these rocks.

At Ormidale, one mile north of the Kyles of Bute, a N.-S. dyke on the slopes of Beinn Bhreac shows these aggregates, however, and is identical with the Tynemouth dyke.

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The augite which is approximately equal in amount to the felspar is light brown in colour and feebly pleochroic. It occurs either in granules or small prismatic grains frequently twinned on the orthopinacoid and usually in sub-ophitic relationship with the small felspar laths. Inclusions of iron-ore are common.

Associated with the augite and occurring sometimes in the interior of the crystal are small pseudomorphs in a greenish-brown mineral resembling serpentine and replacing an earlier pyroxene. This earlier mineral may be referred to the mineral enstatite-augite following the suggestion made by Dr. Thomas and Mr. E. B. Bailey, to account for a similar phenomenon in closely related rocks from Mull.[1]

The iron-ore builds small imperfect crystals and tends to be associated with the augite. Much of it is magnetite or titaniferous magnetite, although from its method of alteration some of it is ilmenite.

The glassy base is small in amount, and forms approximately 10 per cent. of the slide. It is highly charged with iron-ore microlites which impart to it a dark colour, and it is partially devitrified. The texture of the rock is intersertal.

The most westerly of the N.–S. dykes at Craigmore on the foreshore, has characters identical with this dyke but is much thinner.

Thin sections cut from the marginal portion of the Ascog-Kerrycroy dyke show it to consist of an aggregate of turbid felspar laths, patches of iron-ore and much diffused chloritic matter. The felspar laths which form the most abundant constituent of the slide are usually simply twinned and much decomposed. Saussurite is the commonest alteration product.

The augite is not found fresh, but pseudomorphs of chlorite with the characteristic vermicular structure and steel-grey interference colours are common.

Iron-ore occurring in patches is only a little less prevalent than the felspar and tiny grains of haematite occur, scattered throughout the slide.

The most interesting feature of this slide is the frequent occurrence of xenoliths of quartz in groups, consisting of two or three rounded grains associated with the calcite and presumably assimilated from the Old Red Sandstone.

A 12 ft. N.–S. dyke exposed in a quarry in Cnoc Nicoll Wood, Kerrycroy, is very similar to above rock but is slightly finer-

[1] 'Tertiary and Post Tertiary rocks of Mull,' *Mem. Geol. Surv.*, 1924, p. 226.

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grained. The augite shows good crystal form, but frequently has a central core not in optical continuity with its marginal portion. This central core probably represents an orthorhombic pyroxene. The augite is sometimes altered to chlorite. This alteration commences at the periphery of the crystal and proceeds towards the interior, frequently leaving a core of unaltered augite enclosed by a rim of chlorite. Small calcite amygdules occur.

A narrow N.W.–S.E. dyke from the hill-side west of Loch Fad shows some resemblance to the Ascog dyke, but has in addition a small quantity of mesostasial material consisting of a diffused felspathic mass, microlites of pyroxene and little rods of magnetite.

A tholeiite of the Brunton type showing an augmented quantity of interstitial glassy base and a diminished quantity of pyroxene is a narrow N.W.–S.E. dyke at Kerrycroy on the foreshore, a few yards south of the quay. The magnetite is concentrated in the glassy base in the form of little rods and innumerable microlites, imparting to the slide a dense black colour. It also contains small calcite amygdules.

A narrow N.W.–S.E. dyke on the east side of Lyeing Hill and a narrow N.N.W. dyke exposed in the quarry west of the Power Station, Ardbeg, Rothesay, are similar to the above and show the dense black interstitial base with the magnetite drawn out into little rods.

A tholeiite of the Brunton type that shows an approach to the variolites is a 12 ft. N.N.W. dyke on the foreshore at the north end of Scalpsie Bay.

In thin sections it is seen to consist of a few microphenocrysts of felspar and augite with rods of magnetite set in a ground mass of skeletal felspar crystals and small abundant grains of pyroxene. The felspar phenocrysts occur in lath-shaped crystals and consist of bytownite. The irregularly shaped microphenocrysts are fewer in number, and in fact later than the felspar phenocrysts. Magnetite is very abundant, and occurs in elongated rods with a tendency to a stellate grouping. Patches of the ground mass sometimes show a radial structure characteristic of the variolites.

A N.–S. dyke at the north end of Loch Fad, that might be regarded as a basic form of leidleite, can conveniently be described under the heading of the Brunton tholeiites.

In hand specimen it is finely crystalline rock with a greenish-

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grey colour. Sections cut from the central portion of the dyke show it to consist of plagioclase felspar, augite, iron-ore and an augmented quantity of glassy base. The felspar is the most abundant mineral and consists of a labradorite invariably in the form of long narrow prisms with indefinite crystal boundaries. It is generally zoned and twinned on the albite and carlsbad laws. Calcite pseudomorphs after the felspar occur, and one slide exhibited a few large phenocrysts of a slightly zoned labradorite containing dark coloured patches of iron-ore globulites.

The augite is much less abundant than the felspar, and generally occurs in the form of small elongated blades, pale-brown or greenish-yellow in colour, and slightly pleochroic. Iron-ore inclusions in the augite are very common and generally form a fringe to the crystal. In the dark glassy base which almost equals the felspar in bulk, it occurs in the form of little rods composed of adherent octahedra as well as innumerable globulites. A crudely stellate grouping of the felspar prisms and the elongated augite blades impart to the rock a sub-variolitic texture which together with its interstitial glassy base is reminiscent of the basic leidleites.

(ii) *Olivine tholeiites of the Brunton type.* Tholeiites of the Brunton Type with olivine are rare in Bute. The most easterly N.–S. dyke on the foreshore at Craigmore, Rothesay, carries a few rounded olivine grains partially altered to serpentine belonging to an early period of crystallisation. A 1 ft. N.–S. dyke on the foreshore at White Port, Kilchattan, is very similar to the Craigmore dyke.

A narrow N.N.W. dyke of Brunton tholeiite on the east side of Bullochreg Hill has olivine pseudomorphed in iddingsite. This alteration has proceeded from the periphery of the crystal towards the interior, sometimes leaving a kernel of unaltered olivine, and the grains of iddingsite are surrounded by a rim of haematite. Microphenocrysts of augite giving a patchy extinction also occur in this dyke.

A 4 ft. N.E. dyke cutting the Tertiary composite sill west of St. Blane's Hill, carries numerous olivine xenoliths picked up from the complex together with labradorite phenocrysts. The olivine xenoliths are large, show signs of corrosion and have their cleavage cracks lined with serpentine. In one part of the slide olivine has almost enclosed a felspar lath. The felspar phenocrysts of the rock usually show corrosion, but a few fresh

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slightly zoned lath-shaped crystals occur. The ground mass is very fine-grained, and consists of simply twinned felspars of labradorite composition with bifid termination, small rounded grains of pyroxene, and imperfect octahedra of magnetite. Inclusions of the ground mass in the felspars are common.

A rock which may be described as a basic and olivine-bearing variety of Brunton tholeiite occurs as a narrow N.–S. dyke on the roadside, south of Loch Ascog. Macroscopically it is a light grey, fine-grained rock with a tendency to a platey structure.

Under the microscope it is seen to consist of a few microphenocrysts of felspar set in a plexus of felspar laths, augite granules, and abundant olivine. The felspar phenocrysts which occur in laths and tabular crystals, showing both albite and carlsbad twinning consist of an acid labradorite. Inclusions of the ground mass are common, and some of the crystals exhibit a patchy extinction. The bulk of the felspar of the ground mass is oligoclase. The augite is colourless and is the most abundant constituent of the rock. The olivine is fresh and builds small rounded grains. Scattered throughout the slide, and frequently moulded on to the augite and olivine are patches of magnetite. The rocks are holocrystalline with intergranular texture.

(iii) *Salen type of tholeiite.* This type of tholeiite has recently been defined and figured by the Geological Survey Petrographers, and is based upon certain sills of Tertiary Age at Loch Scridain, near the village of Salen, Mull.[1] Olivine becomes an essential constituent of the rock and a mesostasis occurs but is greatly reduced in amount.

A few dykes and two small sills of Salen tholeiite occur in Bute. A wide N.N.W. dyke forming a wall-like exposure near Ardmaleish, north of Kames Bay, is typical of the tholeiites of the Salen type from Mull.

The felspar occurs in two forms, long lath shaped crystals and irregular diamond-shaped plates showing a patchy extinction. It consists of a basic labradorite becoming more acid in the neighbourhood of the mesostasis. Twinning on the carlsbad, albite and pericline laws is common, zoning is feebly developed and inclusions of the pyroxene occur arranged along definite planes. The laths are sometimes curved and the stellate grouping common in the tholeiites of the Brunton type also occurs.

[1] 'Tertiary and Post Tertiary Rocks of Mull,' *Mem. Geol. Surv.*, 1924, p. 371.

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The augite which is as prevalent as the felspar is markedly ophitic towards the latter mineral. It has more colour than in the Brunton varieties, and ranges from a yellowish-brown to pale lilac. It is slightly pleochroic.

Iron-ore which has the magnetite habit is abundant and is associated with the pyroxene.

Olivine is small in amount and occurs in ellipsoidal grains belonging to an early period of crystallisation of the rock. It is always partially altered to serpentine.

The mesostasial matter occurs in definite patches and forms approximately 1/20th of the slide. It consists mostly of a crypto-crystalline felspathic mass, with little rods of magnetite but some patches show a more mature type of crystallisation with definite skeletal crystals of felspar and acicular crystals of augite with the magnetite rods.

A coarser-grained variety of Salen tholeiite showing affinities with the quartz-dolerite occurs in a dyke on the west side of Kilbride Hill. The felspar is a much twinned, slightly zoned, moderately acid labradorite. It frequently occurs in rectangular-shaped sections, twinned in two directions at right angles, and containing abundant inclusions of pyroxene, magnetite ground mass.

A N.–S. dyke, 8 ft. wide at Piperhall Wood on the inland road from Kerrylamont to Rothesay is exactly similar to the above.

The large plates of augite ophitically enclosing the felspar have a lilac tinge, but the colour is irregularly distributed. Olivine is fresher than is usual in rocks of this type and builds rather large grains. The mesostasis is small in amount, and shows an immature type of crystallisation consisting of skeletal crystals of felspar, rapidly crystallised pyroxenes which tend to assume an acicular form and innumerable rods of magnetite. A little quartz occurs interstitially and calcite fills small vesicles.

The multiple N.–S. dyke at Port Lubas, Stravannan Bay, is a Salen tholeiite with a diminished amount of olivine. The mesostasis shows the acicular type of crystallisation of the felspar, magnetite and pyroxene and there is a small amount of interstitial glassy base darkened with microlites of magnetite.

Two small sills of Salen tholeiite occur on the foreshore, south of Kilchattan, one immediately south of Hawk's Nib Point, intruded along the bedding planes of the sandstone, and the other intruded in the lavas a quarter of a mile north of Runnan-

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eun Point. The former of these sills shows in their section little laths of labradorite felspars, a few felspar phenocrysts, with oscillatory zoning and abundant augite and olivine. The augite is ophitic towards the felspar laths and has either a yellow-brown colour or a lilac tinge, and is faintly pleochroic. The olivine occurs in small idiomorphic grains partially altered to serpentine. The mesostasis is small in amount and consists either of glass or its devitrification products darkened by innumerable globulites of iron-ore or of skeletal crystals of felspar acicular augite and little rods of magnetite.

The thin sections cut from the laths of these two sills show it to be very decomposed, consisting of patches of serpentine chlorite and iron-ore set in a matrix of felspar laths. The little areas of the original mesostasial material can still be detected by the rod-like development of the iron-ore.

(iv) *Corrie type of tholeiite.* This type of tholeiite has been defined by Dr. G. W. Tyrrell, and is based upon a group of dykes at Corrie, Arran (5, p. 351). It differs from the Salen type only in being prophyritic and containing a few phenocrysts of basic felspar usually much corroded.

Olivine is confined to the ground mass. One of two representatives of the Corrie type of tholeiite occur in Bute.

A type of Corrie tholeiite showing the ophitic texture developed to a remarkable degree, is a 12 ft. N.E.–S.W. dyke on the foreshore at Kilchattan Bay. The rock is quarried in the face of the cliff bounding the raised beach. The augite is the most abundant constituent of the rock and occurs in large plates ophitically enclosing the felspars or cut into strips by the laths of the latter mineral. It is yellowish-brown in colour, or has a slight purple tinge, and is feebly pleochroic. Sometimes a crystal of yellowish-brown augite is bordered by a band of purple tinged variety. Twinning is rare. Intergrown with the augite in a central position are pseudomorphs after a pyroxene in brown- or green-coloured serpentinous material which probably represents an earlier enstatite-augite.

The felspars are in the form of little laths once-twinned and frequently with bifid terminations and showing a pronounced parallel or radial arrangement. They have the composition of an acid labradorite. In addition to these little felspar laths, there are a few twinned microphenocrysts of felspar of labradorite composition. Glass inclusions are common in these felspars.

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Magnetite occurs abundantly throughout the slide, showing good crystal form. Generally the augite has been moulded on to the iron-ore.

Olivine is far less abundant than any of the other constituents, and is always altered to serpentine. This change commences from the periphery of the crystal, and proceeds towards the interior and shows varying stages to complete replacement.

There is a diminished quantity of glassy base highly charged with microlites of iron-ore and sometimes shows signs of devitrification. Small patches of diffused felspathic matter stained with serpentine probably represent a mesostasis. An analysis of this rock is given later.

A 2 ft. N.–S. dyke at Kilchattan, on the foreshore opposite Brandon Place, is a Corrie tholeiite in which the mesostasis has been almost completely replaced by calcite and serpentinous matter. In some places the felspathic matter of the mesostasis is represented by calcite, and in other cases its original structure is completely obliterated and the mesostasis replaced by a serpentinous pseudomorph.

(v) *Largs type of tholeiite.* This type of tholeiite has been defined and figured by Dr. G. W. Tyrrell (5, p. 353), and is based upon a dyke at the seaside resort of Largs, Ayrshire, on the foreshore three-quarters of a mile south of the Pier.

Tholeiites of the Largs type are represented in Bute by three dykes on the western side of the island. The most northerly N.–S. dyke at Gallachan Bay, in the foreshore, so strongly resembles the dyke figured and described by Dr. Tyrrell (5, p. 351), that an extended description of it is unnecessary. It carries a few large and corroded phenocrysts of bytownite-anorthite felspar with inclusions of olivine and pyroxene zonally arranged. Violet-brown augite is the most abundant constituent of the ground-mass, and is always ophitic towards the felspar laths which consist of an acid labradorite. Magnetite occurs in idiomorphic grains and olivine is abundant both as phenocrysts and in the ground-mass, although it is always partially altered to serpentine. There is a diminished quantity of a black glassy base and spherical vesicles filled with calcite and serpentine also occur.

The middle of the three N.–S. dykes at the northern horn of Stravannan Bay, on the foreshore resembles the above, but has slightly less olivine, which is mainly confined to the ground

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mass. It might be termed a Corrie tholeiite approaching Largs type.

The most westerly of these N.–S. dykes is also a tholeiite of the Largs type. It is much coarser grained than the previous dyke, and contains glomero-porphyritic groupings of much twinned and zoned basic felspar phenocrysts. The augite is colourless or edged with a band of the violet tinged variety, and the glassy base is less than in the previous dyke.

(vi) *Cumbrae type of tholeiite* (*Cumbraite*). Under the heading cumbraite, Dr. Tyrrell has described a very acid type of tholeiite from the island of Great Cumbrae (5, p. 307). It consists essentially of phenocrysts of plagioclase near anorthite in a ground-mass of laths of acid labradorite (Ab1 An1) enstatite, augite and abundant glass. The 6 ft. N.–S. dyke at Runnan-eun Point cutting the crinanite sill is the only representative of this type of tholeiite in Bute.

An extended description of the rock is unnecessary, as it differs only from the type rock in the slightly smaller quantity of its glassy base and the replacement of its enstatite by a greenish coloured pseudomorph.

(vii) *Quartz-dolerites.* A group of dykes occur in Bute that cannot be referred to any of the previously described types of tholeiites. They show affinities with the quartz-dolerites, and will be described under that heading.

A rock representative of several of these dykes is the N.N.W. dyke, exposed in a quarry near Cranslagmorie, south of the Ettrick Bay—Port Bannantyne Road. The dyke is 10 ft. wide, and has a pronounced hade to the south-east in conformity with the bedding planes of the metamorphic rocks of the district.

The felspars exhibit a well-marked columnar habit with a constricted development of their initial portions. For the most part they belong to a later stage of crystallisation than the pyroxene. Twinning on the carlsbad law is very common, and that according to the pericline and albite laws is by no means rare. Zonary banding is general, but inclusions appear less frequently than in the felspars of other types of tholeiites. The extinction angle in symmetrically cut sections varies from the central to the marginal parts, and indicates a variation in composition from a labradorite kernel to an oligoclase rim, but the unzoned varieties consist of a basic labradorite.

The augite is at least as prevalent as the felspar and frequently

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shows a glomero-porphyritic grouping. It occurs in two forms, as hypidiomorphic plates ophitically enclosing the felspar laths, and as blades elongated along the " C " axis. It has a straw-yellow colour, and is faintly pleochroic. Twinning parallel to the orthopinacoid is very common and is generally repeated.

Inclusions of iron-oxide are abundant, especially in the periphery of the crystal, and sometimes form a complete fringe to it. A sahlite structure occurs in some of the augite, especially those elongated along the " C " axis, but is feebly developed, and is generally, although not invariably confined to the interior of the crystal.

The augite is very fresh and unaltered, but intergrown with it, and usually occupying a central position are pseudomorphs in a green or brown serpentinous mineral after pyroxene.

This replacement is usually complete, but in one case a fragment of original pyroxene remained. This earlier pyroxene may be referred to the mineral enstatite-augite.

The iron-ore is abundant, and occurs in octahedra or reticulate skeletal growths, and some of it from its method of alteration is either ilmenite or titaniferous magnetite.

Apatite is absent.

The most distinctive feature of the rock is the mesostasis, which is collected into well-defined areas and shows an immature type of crystallisation.

The mesostasial material consists of patches of skeletal crystals of felspar associated, but not intergrown with slender rods of a serpentinous mineral and numerous tiny octahedra of magnetite.

The patches of skeletal felspar crystals have a tendency to be arranged in a radial or sheaf-like groupings, and sometimes show a definite micro-spherulitic structure. The rods of serpentinous material penetrate these patches, and presumably represent original acicular crystals of pyroxene. Some of the patches show a more mature type of crystallisation in which can be detected irregular shreds, and blebs of quartz inter-grown with the plagioclase felspar, giving a typical granophyric structure.

Towards the margin of the dyke the rock becomes finer-grained, although all the features seen in the central portion of the dyke are preserved. Some of the sections cut from the marginal portions of the dyke exhibit a fracturing and bending of the columnar augites, due to intercrystal pressure at a late stage in the consolidation of the magma.



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Many dykes in the island fall into this group and differ from it only in minor details, for with greater variations these rocks pass into tholeiites of the other types.

A 6 ft. N.N.W. dyke south of Greenan Mill, Loch Greenan, a 4 ft. N.–S. dyke at Dunagoil on the foreshore, a narrow dyke N.W. of Skeoch Wood, Rothesay, a 4 ft. E.–W. dyke at the Bull Loch, and a N.–S. dyke at Stravannan Bay on the foreshore, contain an augmented quantity of mesostasial matter. The Greenan Loch dyke has a little enstatite in addition to the monoclinic pyroxene, and crystals of the latter sometimes have a centre not in optical continuity with their marginal portions. The Skeoch Wood dyke contains black clots of iron-ore microlites, which cross the pyroxene and felspars alike without respect for their crystal boundaries.

The Dunagoil dyke shows a replacement of the mesostasis by calcite. The more immaturely crystallised portions are first affected, and in some cases completely replaced by calcite. This mineral tends to assume a fibrous and radial structure, and sometimes reproduces the original structure of the mesostasis. This dyke has in addition a little, dark, glassy base.

In the N.–S. dyke on the foreshore at Stravannan Bay, the iron-oxide is confined to the mesostasis which occupies half the slide. It is dark in colour owing to the widely disseminated microlites of magnetite, and in places becomes opaque. Larger octahedra of magnetite can occasionally be detected in the mesostasis.

An 18 ft. N.–S. dyke exposed in the Crossbeg Quarry, west of Loch Ascog, resembles the Cranslagmorie dyke, but one part of the slide shows a cervicorn structure of the augite, a very characteristic feature of the tholeiites of the Taliadh type from Mull.

Examples of finger-grained rocks of this type showing a reduced amount of mesostasial material are a 4 ft. N.N.W. dyke exposed in a quarry near Crawshill, south of Barone Hill, two N.–S. dykes at Largizan, and two dykes near Shalunt, on the east side of the Lyeing Hill.

All these dykes have the mesostasis partially replaced by chlorite, and frequently contain micro-phenocrysts of felspar.

Some varieties of tholeiites possess ovoid vesicles around which the smaller felspar laths are tangentially arranged, and into which mesostasial material has oozed at a late stage in the

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consolidation of the rock. In this respect they resemble the Tynemouth dyke, described by J. J. Teall,[1] and the Sgulan Mor Ring-dyke, Mull, described by the Geological Survey Petrographers.

Representatives of this group of rocks in Bute are the N.N.W. multiple dyke at the northern end of Ettrick Bay, on the foreshore, a few yards west of the burn; the N.N.W. dyke one and a half miles south of Ettrick Bay, on the raised beach; an 8 ft. N.–S. dyke at Stravannan Bay, and a 2 ft. N.N.E. dyke at the southern end of Kilchattan Bay.

They differ from the tholeiites previously described in no essential details, so that an extended description of the microscopical characters of their crystalline portions is unnecessary. The mesostasis of these rocks is, however, frequently replaced by calcite, quartz, or serpentinous matter, and these minerals sometimes reproduce its original structure even to the most minute detail.

The mesostasis of the Ettrick Bay dyke is rather more acid than usual, and contains a diminished quantity of pyroxene and iron-oxide, and has a micro-spherulitic texture. Quartz and calcite amygdules occur in this dyke secondary after an original mesostasis.

The slide from the parallel multiple dyke south of Ettrick Bay showed vesicles with a central portion filled with serpentine, surrounded by a marginal area of calcite. The mesostasis had been pseudomorphed in calcite. Serpentinous material had later replaced the calcite in the centre of the amygdule, reproducing the original micro-spherulitic structure, and showing under crossed-nicols the typical black cross.

The mesostasis of the Stravannan Bay dyke has a mature type of crystallisation in which perfect little felspar laths can be seen, but it is much darkened by diffused serpentinous matter. In the more decomposed areas of the slide it is completely pseudomorphed in serpentine.

*Tachylyte.* Tachylyte occurs commonly as a selvage to the tholeiite dyke, but in a N.–S. tholeiite dyke on the foreshore at Stravannan Bay, it occurs as veins an inch or two wide invading the central portion of the dyke. A tachylyte dyke about 1 ft. wide, occurs on the eastern side of the Bullochreg Hill, and the dyke south of Ettrick Bay and the most southerly of the Stravannan Bay dykes, terminate in tachylyte dykelets before they disappear beneath the sand and shingle of the foreshore.

[1] 'The Amygdaloids of the Tynemouth Dyke,' *Geol. Mag.*, 1889, p. 481.

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Thin sections cut from the tachylyte dyke on the eastern side of the Bullochreg Hill show a dense black glass containing a few small but well-formed colourless augite crystals and laths of plagioclase felspar.

The rock is highly magnetic and owes its opacity to the presence of innumerable microlites of magnetite disseminated throughout the glass. In the tachylyte from Ettrick Bay, individual crystals of augite rarely occur. Groups of colourless augite crystals frequently twinned generally enclose ophitically the laths of plagioclase felspar. The dark glassy base is resolved under a higher power into innumerable rods of magnetite associated with skeletal crystals of augite.

This type of tachylyte is common as a selvage to the tholeiite dyke. The Stravannan Bay tachylyte resembles this but is more decomposed; the augite being entirely represented by serpentinous pseudomorphs.

The tachylyte margin of the Kames Hill dyke shows interesting features. The augite which has a pale yellow colour and a high extinction angle occurs as elongated prisms or in plates ophitically enclosing the plagioclase laths. Pseudomorphs in the serpentinous mineral after augite occur. Magnetite occurs as phenocrysts. The junction of the chilled margin of the dyke with the crystalline portion is very sharp.

*Crinanite.* The term crinanite[1] was introduced by Sir J. S. Flett in 1911, for certain analcite-olivine-dolerites in the neighbourhood of Loch Crinan, Argyll, and since found to have a wide distribution in the west of Scotland. They differ from the Scottish teschenites in their much lower alkali percentage, their greater abundance of olivine, the diminished quantity of analcite, and the far less frequent occurrence of apatite. Barkevikite and biotite are typically absent. By failure of analcite, the crinanites pass into crinanite-olivine-dolerites.

According to Dr. G. W. Tyrrell[2] the two types crinanite and teschenite are the parent magmas from which have sprung by differentiation two parallel but tolerably distinct suites of rocks, but Dr. F. Walker[3] has recently given reasons for believing that

[1] 'Geology of Knapdale,' *Mem. Geol. Surv.*, 1911, pp. 116-118.

[2] G. W. Tyrrell, 'Classification and Age of the Analcite-bearing Rocks of Scotland,' *Geol. Mag.*, 1923, pp. 249-60.

[3] F. Walker, 'The Teschenite Sill of Charlestown, Fife,' *Geol. Mag.*, 1926, p. 346.

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this contrast between the two rock series has been over-emphasised.

Typical crinanites and their associated olivine-dolerites are represented in Bute by the large sill that crosses the south end of the island, a 3 ft. N.N.E. dyke on the foreshore at Kerrytonlia and a group of thin N.W. dykes at White Port, Kilchattan. The direction of the thinner dykes of this latter group has been determined by the direction of the bedding planes of the country rock along which the invaded magma has been intruded and their individual dykes may have directions varying from N. to S. and E. to W., but the predominant direction of the thicker dykes is N.W. The small intrusion in the cliffs at the S.W. end of the island is probably a crinanite, but it is very decomposed.

In the hand specimen the crinanites are dark-grey, medium to coarse-grained rocks, but specimens from the centre of the sill are much coarser-grained than the dykes and become almost gabbroidal.

In thin sections the crinanites are holocrystalline, non-porphyritic rocks consisting essentially of felspar, augite, and iron-ores, and exhibiting very little variation in the quantitative relations of their constituent minerals.

The felspar which is approximately equal to the combined augite, olivine and iron-ore is an acid labradorite, but some sections show a felspar of lower refractive index than the Canada balsam. Zonary banding and twinning of the felspar are common but inclusions are much rarer than in the contrasted rocks of the tholeiite type. The twinning is on the albite law, but that according to the carlsbad law occurs although rarely, and pericline twinning is entirely absent. The augite which is remarkably ophitic towards the felspar invariably shows the brownish-purple colour indicative of the presence of titanium and is very characteristic of the rocks.

In the most northerly dyke at White Port, the ophitic structure has reached a high stage of perfection, and in places the augite forms an inter-growth with the felspar giving the myrmekite structure.

The olivine is very abundant, much more so than in any of the tholeiites and occurs in the form of small coarser grains sometimes containing inclusions of iron-ore uniformly distributed throughout the slide. In the dykes on the foreshore at Port Lubas and Kilchattan the olivine is remarkably fresh, but in

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the sill it is partially altered to serpentine. Iron-ore chiefly ilmenitic is very abundant, and tends to be associated with the augite. Little triangular patches of fresh analcite occur between the felspars of the sill, but are sometimes obscured by the presence of serpentine. The sill is a true crinanite, although the dykes fall into the closely related olivine-dolerite group of rocks.

ANALYSES.

| | A. | B. | C. | D. | E. | F. | G. | H. | J. |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ .. | 46.60 | 46.87 | 47.35 | 48.60 | 48.63 | 48.92 | 50.41 | 51.53 | 60.46 |
| $TiO_2$ .. | 1.90 | 2.35 | 1.75 | .70 | 2.32 | 1.88 | 1.30 | 1.57 | .68 |
| $Al_2O_3$ .. | 18.60 | 13.78 | 13.90 | 18.27 | 13.23 | 14.25 | 15.14 | 11.05 | 14.85 |
| $Fe_2O_3$ .. | 3.80 | 3.35 | 5.87 | 3.19 | 3.16 | 1.95 | 2.71 | 2.73 | 1.14 |
| FeO .. | 7.50 | 11.54 | 8.96 | 7.17 | 7.32 | 11.54 | 7.95 | 10.98 | 5.82 |
| MnO .. | .10 | .39 | .23 | .24 | .21 | .27 | .17 | .45 | .10 |
| (CoNi)O .. | — | — | — | — | — | — | — | — | — |
| MgO .. | 6.70 | 4.54 | 5.97 | 6.29 | 7.97 | 5.56 | 6.57 | 5.21 | 7.46 |
| CaO .. | 8.50 | 9.62 | 10.65 | 10.15 | 12.30 | 10.23 | 11.30 | 9.68 | 8.19 |
| BaO .. | — | — | — | — | — | — | .03 | — | — |
| $Na_2O$ .. | 2.40 | 2.55 | 2.73 | 1.63 | 1.20 | 2.67 | 2.29 | 3.48 | 3.27 |
| $K_2O$ .. | .40 | 1.13 | .54 | .45 | 1.13 | 1.01 | .82 | .86 | 2.20 |
| $H_2O > 105°$ | 1.40 | .75 | 1.16 | 1.63 | .65 | .45 | 1.01 | 1.26 | 1.42 |
| $H_2O < 105°$ | 1.90 | 1.02 | 1.04 | 1.60 | .75 | .82 | .72 | .71 | .63 |
| $P_2O_5$ .. | .10 | .14 | .24 | .09 | .01 | .17 | .15 | .22 | .65 |
| $CO_2$ .. | — | 1.26 | .32 | — | — | trace | .07 | .08 | — |
| $FeS_2$ .. | — | .51 | — | — | — | .3 | — | .26 | — |
| S .. .. | .10 | .27 | .23 | trace | — | .16 | .06 | — | — |

Trace of Arsenic in B and F. Trace of Zinc in F.

A. Olivine-tholeiite (Largs type). Arran, quoted 'The Geol. of Arran.' *Mem. Geol. Surv. Scotland*, 1928.

B. Quartz-dolerite dyke, Cranslagmorie, Port Bannatyne, Bute. Analyst, W. H. Herdman.

C. Olivine-tholeiite (Salen type), Mull, quoted 'Tertiary and Post Tertiary Geol. of Mull,' *Mem. Geol. Surv. Scotland*, 1924.

D. Olivine-tholeiite (Corrie type), Arran, quoted 'The Geol. of Arran," *Mem. Geol. Surv. Scotland*, 1928.

E. Olivine-tholeiite Lugtown, quoted *Sum. Prog. Geol. Surv.*, 1925.

F. Olivine-tholeiite (Salen type), 12 ft. dyke, foreshore Kilchattan Bay, Bute. Analyst, W. H. Herdman.

G. Olivine tholeiite (Salen type) Kielderhead, Northumberland. Quoted 'The tholeiite dykes of the North of England.' A. Holmes and H. T. Harwood *Min. Mag.*, 1929, p. 16.

H. Brunton tholeiite, Mull. Quoted 'Tertiary and Post Tertiary Geol. of Mull, *Mem. Geol. Surv. Scotland*, 1924.

J. Tholeiite (Cumbrae type). Quoted 'Some Tertiary Dykes of the Clyde Area,' G. W. Tyrrell (5, p. 305).

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NORMS.

| | B | F |
|---|---|---|
| Quartz .. .. .. .. | .66 | — |
| Orthoclase .. .. .. | 6.67 | 6.12 |
| Albite .. .. .. .. | 21.48 | 22.53 |
| Anorthite .. .. .. | 22.80 | 23.63 |
| Diopside .. .. .. | 13.46 | 21.71 |
| Hypersthene .. .. .. | 19.95 | 10.14 |
| Olivine .. .. .. .. | — | 7.19 |
| Magnetite .. .. .. | 4.87 | 3.02 |
| Ilmenite .. .. .. | 4.41 | 3.64 |
| Apatite .. .. .. .. | .34 | .34 |
| Pyrite .. .. .. .. | .51 | .30 |
| Calcite .. .. .. .. | 2.80 | — |

B. Quartz-dolerite dyke, Cranslagmorie, Port Bannantyne, Bute.

F. Tholeiite, Foreshore, Kilchattan Bay, Bute.

The analysis of the Kilchattan dyke shows it to be closely allied to the tholeiite of the Salen type from Mull. The dyke was referred to the Corrie tholeiites from a slide in the writer's collection from a N.N.W. dyke at Corrie, Arran on the foreshore a few yards north of the Cable Station, and which differs from it only in the possession of rather larger and slightly more corroded phenocrysts of basic felspar.

Among the north of England tholeiites, a slide from the Kielderhead dyke, Northumberland, taken from an exposure in a sike one mile up the east bank of the Scalp Burn, is almost identical with the Kilchattan rock.

It is difficult to place the Cranslagmorie dyke in any scheme of classification of the tholeiites. Petrologically it is a quartz-dolerite resembling in some respects the Palaeozoic quartz-dolerites of the Midland Valley of Scotland. Chemically its closest analogue is the tholeiite of the Salen type. In this respect it differs from the most basic analysed representative of the Permo-Carboniferous quartz-dolerites in its lower percentage of alumina and higher percentage of alkali, and from the

[1] It should be stated that Dr. Tyrrell (5) used the name 'Corrie type' of tholeiite some years before the publication of the Mull Memoir in which tholeiites of the Salen type were defined.

[2] 'Tertiary and Post Tertiary Geol. of Mull,' *Mem. Geol. Surv.*, 1924. 'The Neighbourhood of Edinburgh,' *Mem. Geol. Surv.*, 1910, p. 308.

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Talaidh quartz-dolerite in its lower percentage of silica and alkalies.

Quartz-dolerites of the Salen type have been recorded from Lorne, and are the coarse-grained representatives of the corresponding tholeiite.

The Cranslagmorie dyke can scarcely be regarded as a Salen quartz-dolerite for it is olivine free.

The presence of olivine has been recorded from the marginal modifications of the Palaeozoic quartz-dolerite intrusions, when it is absent from the interior of the intrusion. Olivine is absent, however, from the marginal facies of the Cranslagmorie dyke. The rock may be described as a quartz-dolerite of Cranslagmorie type, and may prove to be very common among the Cowal Tertiary dykes.

The published analyses of the Brunton tholeiites show they are the slightly more acid representatives of the tholeiite family than the Salen and Corrie tholeiites, both of which contain olivine as an essential constituent.

Although in the island of Bute, several distinct types of tholeiites are found in proximity, they are with the solitary exception of the Cumbrae type from Runnan-eun thoroughly basic in composition, and in this respect stand in striking contrast to the corresponding dykes from the north of England, which show a far greater number of rocks of more acid composition.

## VII.—Evidence of the Age of the Dykes, Summary and Conclusions.

The solitary dyke of lamprophyre at the Bull Loch is the oldest dyke in the island. Lamprophyre dykes with a N.E. trend and tendency to form sheets are common in the adjacent Cowal division of Argyllshire, where they are younger than the earth movements which produced the metamorphism of the Highland rocks and older than the N.W. basalt dykes which frequently cut them, and older than most of the faulting. The Bute and Cowal dykes may plausibly be referred to the Loch Etive dyke swarm, which includes lamprophyre dykes of N.E. trend, and has been assigned a Lower Old Red Sandstone Age by the Survey.[1]

The markle and mugearite basalt dykes are co-magmatic with the lavas of Lower Carboniferous age in the island although more decomposed. The majority of these dykes have an E.N.E

[1] 'Geol. of Ben Nevis and Glencoe,' *Mem. Geol. Surv.*, 1916, p. 141.

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direction, although a few favour a N. to S. direction, but there is no evidence of the relative ages of the two groups of dykes. Dykes co-magmatic with the Carboniferous lavas in the island of Great Cumbrae and penetrating them contain more acid rock-types than those that occur in the Bute dykes, as bostonite and trachyte, but both the Bute and Cumbrae dykes are referable to a great series of thin and impersistent dykes that extend in the west of Scotland from Bute to Campsie Fells.

The E.–W. quartz-dolerite dykes of Bute belong to the group of E.–W. quartz-dolerite intrusions that cross Central Scotland, and form a conspicuous feature in its geology. The age of these intrusions is uncertain.

The most southerly E.–W. dyke in Bute is later than the Highland Boundary Fault. The most northerly E.–W. dyke is probably a continuation of the Ettrick Bay dyke displaced by the Highland Boundary Fault. It is cut by a N.–S. tholeiite dyke. This is not inconsistent with an early Tertiary Age for these dykes, especially as quartz-dolerite is a characteristic Tertiary rock-type in the west of Scotland, but the balance of evidence from other parts of Scotland favours a Permo-Carboniferous age for these intrusions.[1]

The crinanite-olivine-dolerite dykes of Bute, like their analogues in Arran and Knapdale, are very localised in their distribution, and do not occur outside the southern third of the island, but unlike the crinanite dykes of Arran they are thin and do not exceed a thickness of 3 ft. These dykes are associated with the crinanite sill in the south of the island of which they appear to be the feeders. They tend to follow a N.W. direction, the direction maintained by these dykes throughout west Scotland, although at Kilchattan Bay a crinanite dyke follows a north-easterly direction parallel to the dykes of Carboniferous age.

The Bute crinanite sill is locally deeply weathered and for that reason, was assigned a Permo-Carboniferous Age by Dr. Smellie,[2] but as pointed out by Dr. Tyrrell, it strongly resembles the Tertiary crinanite sills of South Arran in its coarsely gabbroidal central portions, and its association with a composite intrusion

[1] 'Geology of the Glasgow District," Revised Edition, *Mem. Geol. Surv.*, 1925, p. 150. Also G. W. Tyrrell; "Intrusions of Kilsyth-Croy District," *Geol. Mag.*, 1909, p. 299.

[2] The Survey regarded this sill as Carboniferous, 'North Arran,' *Mem. Geol. Surv.*, 1913, p. 98.



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similar to that of Bennan Head. Its further association with the crinanite-olivine-dolerite dykes gives added support to this view.

The tholeiite dykes of Bute, unlike those of Arran are usually thicker than the crinanite-olivine-dolerite dykes and may attain a width of 40 feet, although they are usually much thinner. South of the Highland Boundary Fault these dykes follow a N. to S. direction, a direction initiated by a few of the Carboniferous dykes, although in the southern third of the island a few tholeiite dykes follow a north-easterly direction, the predominant direction of the Carboniferous dykes. North of the Boundary Fault, the average direction of the tholeiite dykes is N.N.W., although the direction of the individual dykes may vary from N.W. to N.N.E. The direction of these dykes has been controlled by the local variation in the dip of the beds of the metamorphic rocks.

The predominant direction of the Arran tholeiite dykes is N.N.W. to S.S.E., although they vary from N.W. to S.E. and N.N.E. to S.S.W. and a few are even E. to W., directions which correspond closely with those of the Bute tholeiites.

Only a small number of the Clyde tholeiite dykes have been examined in detail, but it is possible to draw certain conclusions regarding their distribution.

Tholeiites of the Brunton type are numerous and widely distributed in the west of Scotland and in the north of England. So far as present knowledge goes, tholeiites of the Cumbrae type are confined to a narrow band trending S.S.E. from the Cowal peninsula through Great Cumbrae, and including the S.E. portion of Bute into Central Ayrshire. Tholeiites of the Salen type are widely distributed in the west of Scotland and north of England and apparently belong to the Mull swarm of dykes. Their porphyritic equivalents, the Corrie tholeiites, however, are very localised in their distribution. Few dykes of the Largs type have yet been recorded, and their areal distribution cannot be defined.

In Tertiary times, South Bute constituted a minor focus of igneous activity subordinate to the Arran centre. The igneous cycle was inaugurated by the intrusion of the crinanite sill and its associated dykes which are probably contemporaneous with those of S. Arran.

An epoch of faulting followed and produced the N.E. to S.W. and N.W. to S.E. faults one of which, the Glen Callum fault, displaced the sill. Igneous activity was renewed in the successive intrusions of the composite sill whose outcrop crosses the fault

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without displacement. The intrusion of the tholeiite dykes and sills was the latest episode in the Cainozoic sequence for at Runnan-eun Point, a N.S. tholeiite dyke cuts the crinanite sill and near Barr Hill a N.E. tholeiite dyke cuts the composite intrusion. Igneous activity ceased before the present surface features of the island were carved, but it is a significant fact that two large valleys of the north of island Glen More and the Balnakailly valley have a N.N.W. trend parallel to the direction of the planes of weakness, along which the dyke material was injected in earlier Tertiary times.

I have to express my thanks to Dr. G. W. Tyrrell for suggesting the work, and kindly allowing me to examine material bearing upon the subject in the Geological Dept., University of Glasgow; to Mr. G. M. Davies, of the Geological Dept., Birkbeck College, University of London, for helpful suggestions and criticism during the progress of the work; and to the Senate of the University of London, for a grant from the funds of the Dixon Bequest which has defrayed part of the cost of this research.

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## No. XVI.—The Sequence in Islay and Jura. By J. W. Gregory, LL.D., D.Sc., F.R.S.

(Read 13th December, 1928; issued 26th April, 1930).

Islay has the special geological interest that the Dalradian rocks there are associated with those that have been identified as Lewisian, Moine and Torridonian, and contain fossiloid impressions that have been regarded as Cambrian. The Dalradian sequence in Islay includes representatives of all the Series to the uppermost division, the Ardnoe Beds, and the Schichallion Boulder Bed. There is still marked disagreement[1] as to the structure of the island and the succession of its rocks. Macculloch in 1819 was the pioneer in Islay Geology (Western Islands of Scotland, Vol. II, p. 223); he compared the western rocks to the Lewisian gneiss, identified those of the northern Rhinns and their continuation in Oronsay and Colonsay as mica-schists, and with characteristic insight correlated the Portaskaig Conglomerate with the Schichallion Boulder Bed and recognised its unconformity on the Islay Limestone. Murchison and Geikie in 1861 (Quart. Journ. Geol. Soc., Vol. XVII, pp. 206-10), believing in the Palæozoic age of the Highland metamorphic rocks, correlated the Islay Limestone with the Durness Limestone (Ordovician) and the upper quartzite with that of Sutherland which is Cambrian. Thomson[2] in 1877 (*Trans. Geol. Soc., Glasgow*, V, pp. 200-222) correlated the gneiss of the Rhinns with the Lewisian, the rocks of north-eastern Islay with the Torridonian, the main quartzite with the Upper Cambrian and the quartzite and schists of the Mull of Oa with the Silurian.

[1] The extent of the disagreement may be shown by the following comparisons of the order in which the horizons numbered 1-11 on p. 437 are placed on different interpretations:—

(a) According to the Survey Memoir on Islay—1, 3, 4, 5, 7, 8, 9a, 6, 10b, 10a, 11, 2, 9b.

(b) According to Mr. E. B. Bailey (1917)—1, 10b, 7, 8, 9, 10a, 11, 5, 4, 3, 2, 9b.

(c) According to Mr. J. F. N. Green of the beds included in his memoir (1924)—1, 6, 10a, 12 pt., 11, 9, 8, 7, 1, 9a, 9b, 6, 10a, 7, 8, 9b.

[2] His collection is now in the Hunterian Museum, University, Glasgow.

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He recognised that some of the rocks represent those now referred to as Dalradian, and in his valuable study of the boulder bed, pointed out that some of the " granites " are foreign to the island.

The basis for recent work on Islay is the Geological Survey maps (Sheets 19, 27 and 20) and Memoir (Geology of Islay, 1907) by S. B. Wilkinson with notes by Teall and Peach.

According to the Geological Survey Memoir, eastern Islay consists of Dalradian rocks brought by the Skerrols Thrust over the Torridon Sandstone, which overlies the Lewisian gneiss. According to Mr. E. B. Bailey (1917, The Islay Anticline, *Quart. Journ. Geol. Soc.*, LXXII, pp. 132-159, pl. XII) the Dalradian succession is an anticline, and the southern rocks, which the Survey Memoir identified as the oldest part of the Dalradian, he regards as the youngest. Mr. Barrow (*Quart. Journ. Geol. Soc.*, LXXII, 1917, pp. 159-62) and Mr. J. F. N. Green (*Quart. Journ. Geol. Soc.*, LXXX, 1924, pp. 72-105, pl. V-VI), on the other hand, represent the structure as a syncline, denying the Torridonian age of the sandstones, and the existence of the Skerrols Thrust.

It may be convenient to state at the outset that my own conclusions as to Islay agree most nearly with those of the Survey Memoir. I differ from it, however, by regarding as Dalradian the rocks which it identified as Torridon Sandstone, by not accepting the slaty schist of Central Islay as on the same horizon as the Port Ellen " phyllite," and by considering the quartzite of the south-eastern mountains (the Ben Bhan and Ben Bheigeir group) as interbedded in the Dalradian succession and not as unconformable on the limestone-slate series. I agree with the Memoir in the two fundamental issues, by regarding the Bowmore Grits as thrown against the rocks to the east by a reverse fault, and by accepting the Dalradian strata as in an ascending succession from Port Ellen on the southeast to the dolomites and quartzites of the northern end of the island.

The oldest rocks on Islay are the basic gneisses of the southern end of the Rhinns, the peninsula of western Islay. These gneisses were recognized by James Thomson as Lewisian. I have only seen them on their northern margin, and the microscopic character of the specimens collected is not that of normal Lewisian gneiss. Sir Jethro Teall in describing the rocks referred to the Lewisian, remarked that " it is difficult to speak with confidence " as to their original character; he adds, they were probably " not dissimilar from those occurring in areas of Lewisian

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gneiss"; he notes, however, their difference from the normal Lewisian (Islay, 1907, p. 15). Wilkinson described planes of schistosity as common to both the Lewisian and the Torridonian at the junction of the two (*Ibid.*, p. 18); if so the present structure of the Lewisian is later than the deposition of rocks assigned to the Torridonian. The rocks in hand specimens are certainly Lewisian in aspect. I have not seen enough of them to express any opinion as to their character, and they are here accepted as Lewisian in deference to the conclusion of the Geological Survey.

Unconformable on the Lewisian are schists, which are predominantly green and epidotic, with some black fine-grained mica-schists. They were originally no doubt grits, graywackes and mudstones, of material mainly derived from the Lewisian gneiss. They have been altered into fully foliated contorted schists. They are doubtless, as identified by the Survey, the continuation of the rocks of Colonsay and Oronsay, but their identification as Torridonian appears to me highly improbable.

MacCulloch (Western Isles, 1819, Vol. 1, p. 260) described the predominant Colonsay rock as a "micaceous schist, often approximating to chlorite slate and to clay slate, and presenting a smooth and glossy surface," and as a rule conspicuously contorted. MacCulloch dismissed the Colonsay rocks briefly, as he said they were of a type he had sufficiently described elsewhere; and this description was not of the Torridon Sandstone. His view that the rocks of western Islay are a schistose series is fully correct. The Survey Memoirs describe them in western Islay, Colonsay and Oronsay, as sheared, schistose, mylonized, bent by innumerable folds and puckers, and "intensely puckered and cleaved" (Mem. Islay, 1907, p. 24; Mem. Colonsay and Oronsay, sh. 35, 1911, p. 25). Some of the rocks have been affected by a double cleavage. They contain cleaved flags (the Kiloran Flags, Mem. sh. 35, pp. 14-15), which are compared to the Moine though less altered, also abundant pegmatites, cleaved dyke rocks (lamprophyres) and secondary hornblende in the epidotic beds.

The references to the rocks as mudstones and sandstones give an impression favourable to their identification as Torridon Sandstone; but the Memoir remarks that the term sandstone is used with hesitation, as it is not generally applied to such "thoroughly compacted" cleaved rocks (Colonsay Mem., 35, 1911, p. 14).

The Kilchiaran are the typical rocks, and they appear quite

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different from the Torridonian. The Colonsay Memoir (1911, p. 16) remarks of them that " neither to the North nor the South do we find a sequence of beds at all similar in its details."

The differences between these rocks and the Torridon Sandstones appear far to outweigh the resemblances. The Torridon Sandstones are a thick series of unfoliated grits, sandstones and conglomerates, which are typically chocolate in colour, and usually have a gentle dip. These Islay rocks are foliated and schistose, are mostly green mica schists, have steep dip, and are highly contorted. The essential difference between the Torridonian and Dalradian is that the Torridonian were laid down after the earth movements which produced the foliation and metamorphism of the Dalradian rocks. Narrow bands of the Torridon Sandstone are altered and even mylonized along the thrust places; but the main mass of the formation shows no regional metamorphism, either thermal or dynamic. The schists of Colonsay and western Islay have been subject to the same metamorphism as the Dalradian—for Barrow even claims them as Moine—while the Torridon Sandstone has not been affected by that change.

The difference between these schists and the Torridon Sandstones may be realized from the description of the latter by Sir Archibald Geikie (Explan. Notes Geol. Map Scotland, 2nd edit., 1910, p. 13) as " a thick pile of reddish or chocolate-coloured sandstone, . . . . . The stratification of these rocks is usually nearly horizontal." The Memoir on the Northwest Highlands (1907, p. 272) states that " the prevalent lithological and stratigraphical features of the Torridonian Series are the uniformity of composition and fresh appearance of the rocks, and the regularity and generally undisturbed character of their disposition "; and it remarks that it is difficult to realize " that such unaltered sediments . . . . are the oldest recognizable sedimentary deposits in the British Isles." It is, of course, true that the comparison of the Islay rocks has been with the altered representatives of the Torridon Sandstone where, as in the Sleat of Skye, they have been mylonized along thrust-planes. But beside the great thrust-planes the altered rocks (N.W. Highland Mem., 1907, pp. 286, 288-90, 351, 361) are mylonized only in narrow bands, and there is nothing in the Torridonian like the widespread metamorphism of the schists of western Islay and Colonsay.

The schists of western Islay are bounded eastward by a fault which is regarded by Mr. Bailey as a continuation of that of the

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Great Glen; but that fault has no marked metamorphic effect. No adequate cause for the shearing of these rocks into schists has been advanced, if they are Torridonian in age. Hence I regard the schists of Colonsay and the Rhinns of Islay as Lower Dalradian. These schists are not like those in eastern Islay or on the mainland, because they are largely made up of Lewisian debris. As they are highly altered green schists and schistose grits, have abundant mica and chlorite and occasional limestone, and have been intensely puckered by dynamo-metamorphism they most resemble part of the Loch Lomond Series.

If these schists be included in the Torridonian the usual definitions of that System and conception of its relations to the pre-Cambrian earth movements must be fundamentally revised. *The Bowmore Flags* (*Green*), *or Bowmore Grit* (*Mem. Geol. Surv.*) or *Bowmore Sandstone* (*Bailey*), (*Moine of Barrow*). The Torridonian age of these unfoliated grits is more probable than that of the western schists. They differ, however, from the Torridon Sandstone as they consist of greenish grits, interbedded with dark green slate, and are in places a compact gray quartzite of Upper Dalradian type. The Survey Memoir (Islay, 1907, pp. 19, 25), describes the rocks as " red, green and gray grits " with, in the upper part, fine-grained slaty and phyllitic bands. The rock south of Bridgend it describes (*Ibid.*, p. 27) as " a purplish fine-grained grit with some slaty bands." Mr. Bailey (1917, p. 138) describes the rock as " compact hard fine-grained sandstone, weathering with brown surfaces, but gray on a fractured face." He further says " they are much shattered as well as considerably sheared." The rock at Laggan he describes as a fine felspathic quartzite. In my field notes I referred to the rocks as consisting as a whole of light gray, very compact quartzite, with occasional layers crushed to sericite-schist, and as very similar to the upper Dalradian Quartzite, but unlike any Torridon Sandstone that I have seen. Mr. Green (1924, p. 84) insists on the lithological identity of some of the Bowmore rocks to the flaggy grit above the Portaskaig Conglomerate, and he correlates them with the flaggy dolomite quartzite series of northern Islay. Mr. Bailey declares this correlation amazing (in Green, 1924, p. 102); but it appears far less improbable than the inclusion of the Bowmore Grits and the schists of western Islay in the same group. I agree, however, with Horne and

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Mr. Bailey that the Bowmore Grits are separated from the flaggy quartzites north of Portaskaig by the Loch Skerrols fault. That fracture, however, seems to me an ordinary reverse fault and not a thrust plane. Messrs. Green and Barrow deny its existence, but though too much has been imposed on it, I believe it is there. The rocks beside the fault are well seen in some crags of white slightly felspathic quartzite near Knockdon Farm, near Bridgend; the rock is intensely crushed, with some planes of movement with a dip of 15 degrees to the east; the most conspicuous faults are nearly vertical with narrow strips of fault rock, in which the downthrow was on the eastern side and the pressure before vertical faulting was from the north-west.

Mr. Green (1924 p. 74) has called attention to two points which tell against the Torridonian age of the Bowmore Grits. First, the presence of the epidiorite sills; and though sills of basic igneous rocks might occur in the Torridon Sandstone, those in the Lewisian rocks of the north-west of Scotland are cut off abruptly against the Torridon Sandstone, and basic igneous rocks in the Torridonian should be less altered than the epidiorites in the Bowmore Grits.

Second, Mr. Green has found in the Bowmore Grits at Black Rock pebbles of the " red syenite " (nordmarkite) which is the characteristic inclusion in the Portaskaig-Schichallion boulder bed. Mr. Bailey points out that its presence may only prove that the Torridonian received its material from the same source as the Portaskaig Conglomerate; yet this evidence is in favour of the Bowmore Grits being of approximately the same age as the Portaskaig Conglomerate. The objection to the inclusion of the Bowmore Grits in the Torridonian is less fundamental than for the schists of western Islay; but in view of the identity shown by Dr. Green's detailed petrographic description of the Bowmore Grits with those of the Portaskaig Series, the presence of the epidiorites and of the nordmarkite pebbles, it seems more reasonable to correlate these gray quartzites with the similar adjacent Dalradian rocks than with the dissimilar chocolate-coloured Torridon Sandstone of 80 miles away. It may be said that the differences between the Bowmore and Torridonian Sandstones may be due to this distance. But why correlate the Bowmore Grits with a distant rock from which it is strikingly different, when there are adjacent rocks identical in character ?

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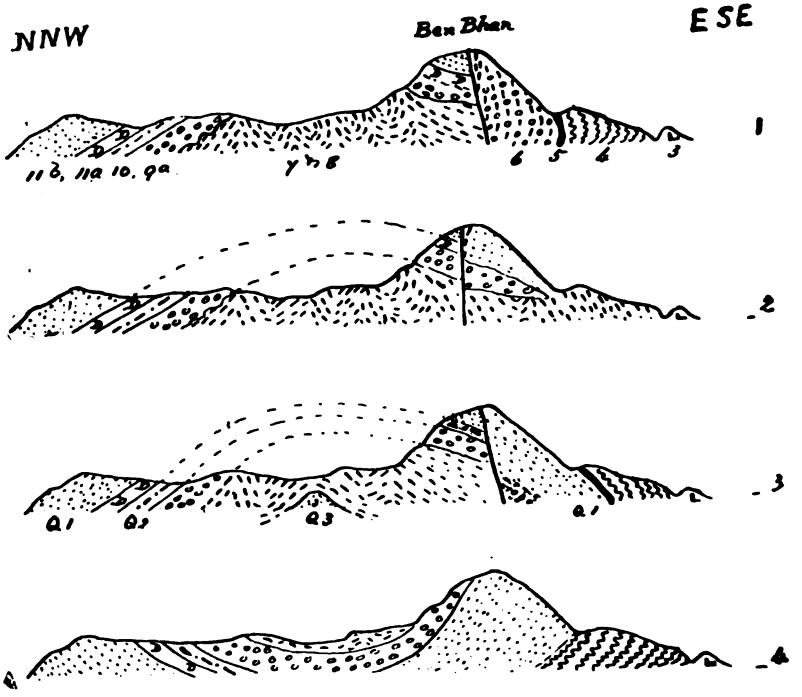


Fig. 2. Sections from the northern coast of Islay, east of Loch Gruinart thro Ben Bhan to the southern coast, west of Ardmore, illustrating diagrammatically the sequence and structure according to No. 2, the Geological Survey; No. 3, Mr. E. B. Bailey; No. 4 Mr. George Barrow; and No. 1 the author.

Nos. (of p. 437).

| | | | |
|---|---|---|---|
| 11b | | Upper Quartzite | Schiehallion Series |
| 11a | D-D | Dolomite Series | |
| 10 | | Lower Quartzite of the northern series | |
| 9a | | Portaskaig Conglomerate | |
| 7 & 8 | | Islay Limestone and Black Schist | Blair Atholl Series. |
| 6 | | Jura Quartzite | Ben Lawers Series. |
| 5 | | Jura Slate | |
| 4 | | Port Ellen Schists | |
| 3 | L | Laphroaig Quartzite-biotite Schists | |

In No. 3, Q1, Q2 and Q3, three distinct quartzites according to Mr. Bailey of which Q1 is 11b in above; Q2 is No. 10; the outcrop to the west of No. Q3 is part of No. 10.

Scale horizontal 1 inch = 4 miles; vertical 1 inch = 2,000 ft.

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The support by Peach of the Torridonian age of the rocks of Islay and Colonsay is not surprising; for it would be in accordance with his view that the Moine gneiss is altered Torridon Sandstone and establish the existence of schists intermediate between these formations. I think Dr. Horne was fully justified in his insertion on the maps of Islay and Colonsay of a query after the " t " by which the rocks are indicated as Torridonian.

*The Dalradian Sequence in Islay.* The feature in the Dalradian rocks of Islay which impresses me as most significant is the agreement of their sequence with that of the main Dalradian belt of the mainland. They include representatives from the Ben Lawers Series to the uppermost Dalradian—the Ardnoe beds near Crinan.

Along the south-eastern shore of Islay the quartz-biotite-schists, which are in places coarse and gneissose, and the mica-schists, contain many epidiorite sills. The quartz-biotite-schists have been called the Laphroaig and Ardmore quartz-schists. North of them are the Port Ellen " Phyllites," a belt of fine-grained puckered sericite-schists, with many veins and irregular lenticular inclusions of vein-quartz; these schists pass into gritty quartzose schists and include some calcareous and dolomitic schists.

These Port Ellen rocks agree in their essential characters with the schists of the Ben Lawers Series, with the western continuation of which, the Ardrishaig " Phyllites," they are correlated in the Survey Memoir (Islay, 1907, p. 9). In line with them in eastern Shuna is a band which Mr. Bailey, though differing as to the age of the Port Ellen Phyllite, identifies as Ardrishaig Phyllite. On the northern edge of the Port Ellen schists is a thin band of a " graphitic schist," which is the western extension of a band that occurs along the eastern coast of Jura and is Mr. Bailey's " Jura Slate." It is associated with his " Scarba Conglomeratic Group " (Bailey, 1917, p. 154). This graphitic schist is on the horizon of the graphitic Ben Eagach schist or black-schist, which lies below the Cammoch Hill Quartzite and above the Ben Lawers Schist near Pitlochry.

Northwest of the Port Ellen " Phyllite " is a band of schistose grits and felspathic quartzites, from half a mile to three miles wide. It contains much argillaceous material on its eastern side near Port Ellen, where it passes into the Port Ellen " Phyllite " by a series of interstratified quartz-schists and " phyllites."

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*The Jura Quartzite.*

The mountains of southeastern Islay are formed of a quartzite band that lies along the southern side of the Mull of Oa Peninsula, passes north of Port Ellen, and is cut through by the southern half of the Sound of Jura. Its continuation forms most of the long island of Jura. Various names have been given to this rock. It is called the Main Quartzite of Islay, both in the Survey Memoir and by Mr. Bailey, as the quartzites of north-eastern Islay were regarded as part of it. It is referred to in the Survey Memoir as the Ben Bhan Quartzite; but that name is indefinite as there are two quartzites on Ben Bhan. The term Southern Quartzite is unsuitable as the Laphroaig and Ardmore quartzites are further south. As this quartzite forms most of Jura it is referred to as the Jura Quartzite.

The Jura Quartzite in Islay is well seen on the road to Bridgend, for two miles north of Port Ellen. The first outcrop is in some crags to the north of Rosalind Cottage, just opposite the Distillery Road. The rock there is a coarse conglomerate crowded with quartz pebbles an inch in diameter. The small quarry immediately to the north is in coarse schistose grit, with the pebbles seldom more than quarter of an inch in diameter. An intercalation of black slaty schist is seen both on the shore by the distillery and in a lane east of the main road. This black schist is identified by Mr. Bailey as the " Jura Slate." Thence northward numerous exposures show fairly coarse, speckled, brown weathering pebbly schistose grit; the materials gradually become smaller towards the north, and include occasional films of phyllitoid. In the quarry beside Balaclava House occurs a evenly banded quartzite similar to that in the cave in Jura a mile south of Feolin Ferry. Further north bands of vitreous fine-grained quartzite, with felspathic grains of the size of pin-heads, are intercalated with coarse brown schistose grit; the fine-grained quartzite increases in amounts to the north. Opposite the wood, Druim Iriseig, 1¼ miles from Port Ellen, the rock is highly schistose, being sheared into flat lenticles and the felspar has been nearly all altered into muscovite. Still further north, in the exposures beside a peat bog, the quartzite becomes clean and white, and very different from the brown speckled, dark-coloured coarse schistose grit to the south. This white clean quartzite is also shown in a quarry north of the wood, west of the road.

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East of the road the quartzite is in one place shattered and traversed by quartz veins and bands altered by secondary silification obviously due to a fault. At Leorin, about two miles from Port Ellen, the quartzites are succeeded by black schist and

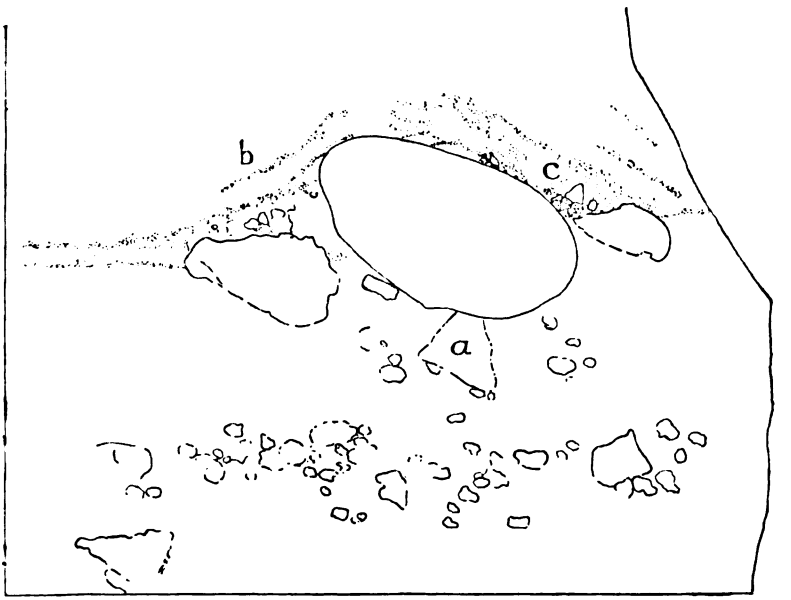


Fig. 3. A block of Jura Quartzite from a small roadside quarry N. of Jura House, showing a layer of fine-grained, falsebedded quartzite above a coarser band with small pebbles and separated by a pebble layer. The upper layer in the figure, which was to the west, is shown to be the younger by:—

1. the position of the quartz pebble *a* which would not have been balanced on its point in a current strong enough to have carried the coarse pebble material in which it lies.
2. the pebble patch below *b* in the lee of the large pebble.
3. the bedding in the quartzite curving up against the large pebble; some layers end against it. The falsebedding here is due to the current flow from N. to S., i.e. from the right of the figure and the sand being deposited against the pebble.

Magnified 2½ diameters. Drawn by W. J. McCallien.

limestone. The quartzite is well exposed 200 yards from the contact and Mr. McCallien found one exposure in situ 100 yards from it. This rock is a clean fine-grained vitreous quartzite with minute felspar grains and some muscovite.

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The traverse from Port Ellen to Leorin shows no obvious repetition. The beds all have a regular steep dip to the S.S.E.; and though there may be some folding or repetition by faults I saw no evidence of such. The quartzite appears to be one continuous series not less than 5,000 ft. in thickness. The southern side appears to be the oldest, as it begins with a coarse basal conglomerate; it is interbedded with a layer of phyllitic schist; and the quartzite is impure and weathers brown. The northern part is clean, white and highly schistose. Mr. G. Barrow has called attention to the significance of this contrast, which is often seen in the Highlands, where the lower edge of a quartzite may contain abundant detrital material, and the rock is purer and cleaner in the upper layers. Although the Jura Quartzite has a steady dip to the S.S.E. the rock on that edge is the older and the whole mass has been overtilted. According to the Survey and Mr. Bailey the northern edge of the Jura Quartzite is the base. The contrary view, held by Mr. Barrow and myself is supported by the position of some of the pebbles. Thus in a banded specimen from Jura (fig. 3), collected by Mr. McCallien and myself north of Jura House, and now in the Hunterian Museum, a small quartz pebble lying on its base above a conglomeratic band has the bedding so arranged against it as to show that the northern side of the specimen was the top.

The Jura Quartzite agrees both in character and position with the Cammoch Hill Quartzite, which in my classification of 1910 is placed as the upper member of the Ben Lawers Series. According to the Geological Survey Memoir (pp. 8, 35, 36) however, this rock is the youngest member of the Dalradian Series in Islay; for Wilkinson regarded it as the continuation of the quartzites which farther N. overlie the Portaskaig Conglomerate. Mr. Bailey adopts the same correlation, but regards the two quartzites as the middle part of the Islay Dalradians. Wilkinson claimed that this Jura Quartzite overlies the Islay Slate and Limestone, and such is the natural interpretation of the Survey Map, Sheet 19. For instance a forked band of limestone just west of Lake Allallaidh (6° 7′ W, and 55° 45′ N) strikes parallel to the edge of the quartzite and tapers out just before reaching the higher ground of the Portaskaig Conglomerate and quartzites, as if it were parallel to the edge of the quartzite and tapers out just before reaching the higher ground of the Portaskaig Conglomerate and quartzites, owing to being cut off by their overlap. Similarly

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farther W. the Islay Limestone for two miles to the N.E. of Leorin is mapped as parallel to the edge of the quartzite, and is suddenly cut off by the projection of the quartzite to the N. A mile and a half further N. the limestone at Maol Airidh o Dhuin is mapped as a tongue exposed by denudation of the adjacent quartzite. Mr. Wilkinson's mapping of the northwestern edge of the quartzite, represents the quartzite as unconformable to the black schist-limestone series. There is however, no evidence of any similar unconformity on the southeastern edge of this quartzite, and the junction there is consistent with the interstratification of the quartzite with the schists to the S. The apparent contradiction between the two edges of this quartzite band is, I believe, due to Mr. Wilkinson having included in it two distinct quartzites. The map shows a sudden great increase in width of the quartzite belt where, after its long course parallel to the limestones, it cuts across them in a great bulge northward. This northern projection contains epidiorites, which are absent from the main band to the S.; and the quartzites of the two areas are very different in character. Mr. Wilkinson is probably right in his identification of the quartzite in this expansion with the northern series; he is also, I believe, right in his view that the Portaskaig Series is unconformable on the limestone series near the Mull of Oa; but at Ben Bhan the northern quartzites are probably unconformable on the Jura Quartzite.

The most instructive section across the northern quartzite is in the deep gorge of the Uillt Ruadha, which, according to the map and memoir traverses a broad band of the Portaskaig Conglomerate, which is followed to the S. by a quartzite and a broad band of epidiorite and then by the Jura Quartzite. At the foot of the Uillt Ruadha gorge the Islay Limestone and black schist are well exposed; then at the level of about 600 ft. is a thin band of the Portaskaig Conglomerate containing pebbles of schistose quartzite, limestone, and the red syenite which is its characteristic rock. This band of conglomerate is lower and more to the N.W. than the edge of the conglomerate as marked on the map. On climbing up the gorge with Mr. McCallien, we were surprised not to find any further specimens of the boulder bed. The rocks are variable quartzites, sometimes calcareous, gritty sandstones, and remarkably different from the compact schistose Jura Quartzite. At about 950 feet the gorge cuts through flaggy quartzites similar to those of the northern end of the island. At about 1050 ft., above

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the upper end of the gorge, some crags to the W. consist of gritty calcareous quartzite, with a sandy base and small pebbles; and among them I found quartzite with the rounded marks, which in the northern part of the island have been described as annelid pipes. The next conspicuous exposures are of epidiorite followed on the plateau around the summit cairn of Ben Bhan by a litter of quartzites, including a clean vitreous variety with felspars of the size of pin-heads, and a pink-weathering, regularly-banded quartzite like the Upper Quartzite of northern Islay and that in the cave on the shore of Jura, a mile south of Feolin Ferry. South of the summit of Ben Bhan is a band of schistose quartzites and grits.

The Survey Memoir refers to the occurrence " one-third of a mile N.N.W. of the summit of Ben Bhan, not far beneath a sill of epidiorite, of annelid borings similar to those found in the northern area." This pipe-quartzite exactly corresponds in position to that previously referred to from the western side of the Uillt Ruadhə. Though I did not find any boulders in the main part of the quartzitic sandstones of the Uillt Ruadha, Wilkinson seems to be fully justified in identifying those rocks with the Portaskaig Series. They appear to be a distinct series from the massive compact schistose quartzites and grits of the Jura Quartzite to the S.

The relation of these Portaskaig rocks of Ben Bhan to the Jura Quartzite is uncertain. It may be an unconformity or a fault, for three quarters of a mile W. of the summit of Ben Bhan, on the northern shore of an un-named lochan, the Geological Survey map colours a plano-convex strip as black schist and limestone. The Survey Memoir, p. 41, however, abandons this identification, and describes the rocks as a rusty shale and cream coloured dolomites, and identifies them with the fifth division of the northern series; it refers in support of this conclusion to the occurrence close by of a ripple marked quartzite with the worm casts belonging to bed 4 of the northern series. At the N.E. corner of this lochan are exposures of a black graphitic schist, which appears to me so similar to that of the Islay black schist, as to justify the identification of the Geological Survey Map; and the limestones at the N.W. end of the lochan seem to me to agree with the Islay Limestone. On the western side of a small pool 100 yards N.W. of this lochan is a red massive limestone similar to some Islay Limestone. According to the Geological Survey Map this strip of Islay Limestone and Black Schist is faulted against the Jura Quartzite,

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which is well exposed on the southern side of the lochan; but according to the Memoir, this strip of limestone and schist is part of the northern quartzite. Either view supports the separation of the rocks on the northern slopes of Ben Bhan from the main quartzite to the S.; but the map seems the more correct and supports Mr. Bailey's section (1917, pl. XII, fig. BB), which shows the two quartzites separated by a fault.

Southwest of the unnamed Lochan a narrow bed of the Portaskaig Conglomerate is shown between the quartzites and the black schists at the height of 700-800 ft., across the head of a small tributary on the right bank of the Abhuinn Bhogie. The exposures there are poor, but hollows in the peat show slabs of sandy calcareous grit with small quartzite pebbles; and they support the evidence of the map as to the extension of the Portaskaig Series on the western flank of the Ben Bhan group.

The difficulties in Wilkinson's interpretation are removed if the Portaskaig Conglomerate at Ben Bhan be later than the schistose quartzites to the S., for then the Jura Quartzite falls into place as part of a series ascending from S.E. to N.W.

BLACK SCHIST AND LIMESTONE (The Blair Atholl Series).

North-west of the Jura Quartzite is a broad belt of black schists which have been used as slates, and are known as the Islay Slate or "phyllite." They have been called the "Esknish Slates" from the locality on Islay, where they were worked. They are coloured black by graphite. Mr. Green (1924, p. 77) says they are not schists, and resemble Paleozoic slate. The specimens which I have examined microscopically are fine dark sericitic schists, and agree in essential characters with the black schists of Blair Atholl, though containing less authigenous material. They are interstratified with the Islay Limestone, of which the most remarkable feature is its widely distributed and well preserved oolitic structure. This limestone, from its characters and position, is representative of the Blair Atholl Limestone, and this conclusion is that of the Geological Survey Memoir, which correlates this limestone with that of Lismore (Mem. Islay, p. 9). The Geological Survey Memoir regards this "central Phyllite" as the continuation of the southern or Port Ellen "Phyllite," and remarks that the two series are identical as regards metamorphism. Mr. Bailey (1917, p. 156) on the other hand, denies this correlation and claims that the Port Ellen "Phyllites" are the more strongly metamorphosed; and I fully agree with him in this opinion.



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THE SCHICHALLION AND ARDNOE SERIES. Along the north-western edge of the Islay Black Schist and Limestone is the Portaskaig conglomerate which Macculloch identified with that of Schichallion. Thomson (*Trans. Geol. Soc., Glasgow*, v, 1877, p. 211) agreed, and suggested the glacial origin of the conglomerate a view accepted by Mr. Green (1924, p. 79), but rejected by Mr. Bailey (1917, p. 142). The general character of the bed appears to me that of a coarse torrential wash. I have seen in it neither striated nor glacially faceted stones. It is interstratified with coarse sandy beds and some dolomites, which may be the source of the dolomite pebbles in the conglomerate.

The identification of this conglomerate as the western extension of the Schichallion Boulder Bed is consistent with its stratigraphical position. It is accepted by everyone except Mr. Green, as being later than and unconformable upon the Islay Limestone and Black Schist. The presence in it of abundant fragments of the Islay Limestone, including the oolitic variety, as well as of the southern schistose quartzites, seems to me conclusive. The main argument to the contrary is the presence of dolomite, which Mr. Green regards as derived from the dolomites to the N.; but they are as well explained as fragments of the dolomite interbedded in the conglomerate series.

Above this western representative of the Schichallion Boulder Bed occurs a series of white, granular, massive, unfoliated quartzites with minute felspar grains; some hand specimens, as from Caol Ila, agree exactly with the Schichallion Quartzite. Above this rock is a series of dolomites and flaggy quartzites, which contain "pipes" and the structures that have been identified as worm casts, and have led to the comparison of this series with the Cambrian Quartzites of Sutherland. These structures seem of the same nature as those in the Ben Lawers "Phyllite" near Inverary that were described as worm tubes by the Duke of Argyll (*Proc. R. Soc. Edinb.*, vol. XXI, p. 30). They do not seem to me evidence of a Cambrian age.[1] These flaggy quartzites with the same pseudo-fossils occur on the shore S.W. of Crinan, and were described as the Ardnoe beds (*Mem. Geol. Surv.*, Seaboard of Mid-Argyll, sh. 36, 1909, p. 33-4) and their superposition on the Schichallion Quartzite shows that they are either the upper beds of the Schichallion Series or belong to a later series. Their close association with a white massive quartzite of the Schichallion type renders convenient their inclusion in

[1] Their pyritic association is no evidence against their organic origin.

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the Schichallion Series. As to the sequence of these North Islay rocks, I agree in general with the Survey Memoir (Mem. Islay, 1907, p. 42) and more fully with Mr. Bailey (1917, p. 148).

*The Maol an Fhithich* Quartzite. This quartzite illustrates the divergence of view between Bailey's anticlinal theory and that of the Geological Survey Memoir; for this rock, according to Mr. Bailey, is the oldest in the Islay sequence, and forms the axis of his Islay Anticline. According to the Survey, the quartzite is faulted against the slate, and is a " typical " Ben Bhan quartzite (Islay, 1907, 35, 68). If the correlation is with the Jura quartzite I agree with Mr. Bailey in his dissent; but if it means that the quartzite is a typical representative of the northern quartzites, as seen in the northern part of Ben Bhan I concur with it.

Mr. Bailey seems to me correct in his view that the Maol an Fhithich Quartzite is essentially distinct from the Jura Quartzite. It begins on the east with a white vitreous fine-grained rock with a very disturbed strike. The black schists cross the valley of Lower Glenastle and are thrown up in Creag Mhor on the western front as if by a fault. From this crag to Upper Glenastle the strike of the rocks is approximately E.N.E. to W.S.W. with a dip to the N.N.W. The broad grass-covered valley between the quartzite and the crags of black schist may hide the fault that is marked on the Survey Map. The existence of a fault there is consistent with Mr. Bailey's statement (1917, p. 140) that the quartzite " near its junction with the phyllites is intensely sheared." The quartzite nearer the western coast is flaggy with the predominant strike to about N.N.E. Some of this quartzite includes films of green slate, and on the cliffs facing the sea the quartzite is conspicuously flaggy with layers of phyllite and pebbles of slate. The coast is very jagged and irregular, with spurs, pinnacles, and caves. The weathering is similar to that along the north-western coast of Islay to the west of Gortantaoid Point. The similar weathering on that coast is shown in a sketch by Peach[1] (Islay Mem., 1907, p. 51).

This Maol an Fhithich Quartzite appears to be " the lower fine-grained quartzite " of Bailey[2] (1917, pp. 147-50) and part of " Group 2 " of the Survey Memoir (Islay, pp. 42, 51). The Maol

[1] That drawing was inserted to illustrate the isoclinal folding, which Mr. Bailey rejects as due to delusive appearance. I agree with him in seeing no evidence of isoclinal folding in this quartzite.

[2] On Mr. Bailey's map, he calls it the massive fine-grained quartzite but that he does not exclude flaggy quartzite is shown by his inclusion in it of the rock shown in Peach's drawing (Mem. Geol. Surv., Islay, 1907, p. 51).

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an Fhithich Quartzite therefore appears to be the lower part of the northern quartzites and to be faulted against the Black Schists. The Portaskaig beds are very thin in this district, as at Balvicar and Cleit na Baintighearn. The fault between this quartzite and the black schist is probably the continuation of that traced across the island past Sgarbh Dubh-Ben Breac—Loch Cam—Bridgend—and Tallant, and Bailey carries it on, after a throw to the N.E., past Laggan Bridge and Duich to the shore of Laggan Bay.

The traverse therefore from the Maol an Fhithich Quartzite across the Mull of Oa, shows the normal succession of a quartzite of the Schichallion Series to the north, next the Blair Atholl Limestone and Black Schist, and the Cammoch Hill Quartzite and Ben Lawers Schist to the south.

*The Portaskaig Conglomerate.* This conglomerate, according to the Survey Memoir and Mr. Bailey, is unconformable on the beds up to the Islay Limestone and Black Schist. That conclusion seems to me justified by the following evidence:—

1. The presence in that conglomerate of the older rocks, including the limestone both oolitic and compact, and various quartzites including the schistose grits of the Jura Quartzite.

2. That where the conglomerate rests on limestones it is richly calcareous, and passes into a calcareous sandstone. At Balvickar the solution of the calcareous matrix has left some of the rocks in the condition of a rotten stone. In some places the Portaskaig conglomerate contains so many limestone pebbles that it is represented by a separate symbol in the Geological Survey Map.

3. The occurrence of isolated patches of conglomerate along the limestone-quartzite junction.

4. The interpretation of the Survey Map from Leorin to beyond Ben Bhan, with the modification that the great expansion in width of the quartzite belt is due to the representatives of the Portaskaig Series, and also the occurrences of outliers of the northern quartzites, of which three are reported in the Survey Memoir on the northern side of Ben Bhan.

5. The clear evidence of unconformity where the Portaskaig Conglomerate rests on the limestone at Cleit na Baintighearn. Mr. Wilkinson's section and description of that section seem essentially correct. Mr. Bailey (1917, p. 145) has remarked that Wilkinson's section is wrongly drawn; it is certainly diagrammatic and exaggerates the difference in dip between the limestone and

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the overlying sandy calcareous band. The limestone is there in thin bands; cut off above by the overlying laminated calcareous sandstone. One of the bands projects upward, as if, being harder it formed a slight projection which was covered by the calcareous sand. That section seems to me, as claimed by Wilkinson, to prove the unconformable superposition of the Portaskaig Beds on the limestone; the abundance of limestone fragments in the overlying beds and their calcareous matrix are both explained by the material being largely derived from the underlying limestone.

I therefore correlate the Islay rocks, omitting igneous rocks, as follows:—

| | | | | |
|---|---|---|---|---|
| Dalradian | Schichallion Series | Ardnoe Beds | Bonahaven Quartzite | 11b |
| | | | Dolomite Beds | 11a |
| | | Schichallion Quartzite | Lower Quartzite of N. Islay 10a) and Maol an Fhithich Quartsite (10b) | 10 |
| | | Schichallion Boulder Bed | Bowmore Grit | 9 |
| | | | Portaskaig Conglomerate and Sandstone | 9a |
| | Blair Atholl Series | Blair Atholl Limestone | Islay Limestone | 8 |
| | | Schist | Islay Black Schist | |
| | | | Mull of Oa Phyllite of Bailey | 7 |
| | | Cammock Hill Quartzite. | Jura Quartzite | 6 |
| | Ben Lawers Series | Ben Lawers Schists | Jura "Slate" etc. | 5 |
| | | | Port Ellen Schists | 4 |
| | | | Laphroaig Quartz-biotite-schists | 3 |
| | Loch Lomond Series | Green Schists and schistose grits of N. Wn. Islay | | 2 |
| Lewisian? | | Gneiss of South-western Islay. | | 1 |

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This classification and correlation agrees in the main with that of the Geological Survey Memoir, which correlated the Portaskaig Conglomerate with the Schichallion Boulder Bed, the Islay and Easdale Slates, the Islay and Lismore Limestones, and the Port Ellen and Ardrishaig "Phyllites." This classification differs from the Survey mainly by rejecting (1) the Torridonian age of the north-western schists and Bowmore Grits, (2) its correlation of the Port Ellen Schists with the Islay "Slate" and (3) the superposition of the Jura Quartzite on the Islay Black Schists and Limestone and Portaskaig Conglomerate.[1]

From Mr. Bailey's interpretation of the structure of Islay the above correlation differs materially, in spite of many important agreements. He places the rocks which are here regarded as the lowest Dalradian in eastern Islay at the top of the Dalradians. According to him the lowest bed in eastern Islay is the Maol an Fhithich Quartzite, as the central bed of his Islay anticline.

The evidence for Mr. Bailey's anticlinal[2] is not extensive, for he claims but little repetition of the beds on the two sides. His anticlinal structure is illustrated by three sections (1917, pl. XII). The northernmost crosses northern Islay and Jura; on the western side are the upper quartzites with the dolomites and pipe rocks; on the eastern side is the Jura Quartzite, and the Jura Slates; the dolomites are shewn in the section on the southern side, but deep underground and not exposed. The northern and southern quartzites on this section appear to be different formations.

The middle section, through Portaskaig and the southern end of Jura, traverses, on the western side, the schists of western Islay with the Bowmore Grits covered by the northern quartzites and dolomites. On the eastern side is the Jura Quartzite, with the dolomites inserted hypothetically underground, while on the surface are the Jura Slates and the mica-schists and quartz-biotite-schists of the Port Ellen belt.

The southern section across central and southern Islay, shows on the W. a wide outcrop of the Bowmore Grits, covered by overthrust Islay Slate and Limestone; to the E. is the Jura Quartzite and the rocks of the Port Ellen belt. Its only direct

[1] The superposition of the Portaskaig Series on the Islay Limestone appears to me established, despite Mr. Green's ingenious suggestion (1924, p. 95-6) that the case near Losset is based upon a complex series of folds.

[2] Mr. Green (1924, p. 99) has emphatically expressed his disbelief in it.

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evidence for the anticline is the folding in the Islay Slate and Limestone, and some repetition in them does not involve the anticlinal structure of Islay as a whole. The absence of the eastern beds from the western side of his anticline is explained in Mr. Bailey's sections by the Loch Skerrols Thrust; and though I differ from Mr. Green as to the absence of a fault along that line, I agree with him and Mr. Barrow that there is no adequate evidence of any such thrust-plane as that in Mr. Bailey's sections.

*The Succession in Jura.*

The geology of Jura is simpler than that of Islay. Jura consists mainly of a long band of quartzite with a broken thin band of black slate and " phyllites " on the eastern coast and some areas of a different quartzite at the western part of the island and of a flaggy and a pipe-quartzite at the northern end. The geology of the island has been described in the Geological Survey Memoir on Knapdale and Jura (Memoir, No. 28, 1911), and discussed by Mr. Bailey in his paper on the Islay Anticline. The main quartzite of the island consists of a schistose grit and quartzite which, as it constitutes most of the island, is here called the Jura Quartzite. It is well seen on the road from Feolin Ferry along the Sound of Islay to Jura House. The quartzite a mile south of Feolin Ferry is fine-grained and evenly banded, with some bands having a vitreous lustre and felspar grains the size of pin-heads. From the very fine-grained pure quartzite of the western edge there is a gradual increase south-eastward in coarseness and impurity. The rock passes to a coarse grit and fine conglomerate with occasional bands of phyllitoid. The southeastern part appears to be originally the lower. The section across the Jura Quartzite agrees in general character with that N. of Port Ellen (see p. 428). Just on the eastern side of the lodge at Jura House a band of black graphitic schist occurs along the stream. Mr. Bailey has called it the Jura Slate and represents it as the representative of the Easdale Slate. This rock, as seen in microscopic section, is a fine-grained mica-schist, rich in graphite. It has clearly been formed from a clay charged with organic matter, which has been altered into graphitic schist. East of it is a further series of brownish coarse schistose grits, which pass eastward into fine quartz-biotite-schist, and lustrous mica-schist, the so-called " phyllite." The rocks are exposed near Craighouse. North of Craighouse the graphitic slate is exposed along the shore and in a quarry where a black grit, interbedded with it is worked for road metal.

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The extreme south-eastern corner of the island consists of phyllites and epidiorites, which are a continuation of those of Port Ellen.

The Ben Dubh fault of Islay reaches the western shore of Jura at Macdougall's Bay, half a mile south of Feolin Ferry. It is there marked by a huge mass of breccia, on either side of which the rocks are shattered and disturbed.

Northwest of this point the quartzites are described by Bailey as of the vitreous type, and he and the Geological Survey Memoir identify them with the northern quartzites of Islay. The Portaskaig Conglomerate and dolomitic flaggy series are not present in that part of Jura; but at the north end of the island a boulder bed, which is compared with the Portaskaig Conglomerate occurs at Glengarrisdale; Dr. Peach identified worm tubes at Glenostradale, and the flaggy quartzites there are probably a continuation of those of North Islay.

On Jura there is no representative of the Islay Limestone and Black Schist, and only one representative of the Portaskaig Conglomerate. Their absence may be explained by the unconformity between the upper quartzites and the Jura Quartzite.

The Portaskaig Conglomerate, in the form of a coarse boulder bed, is well known in the Garvellachs, and its main course may lie W. of the Jura coast, which it reaches only at Glengarrisdale.

The Jura Beds would then be correlated as follows:—

| | | |
|---|---|---|
| Flaggy and pipe quartzite at the northern end. | = | Ardnoe Beds. |
| Vitreous black quartz N. of Feolin Ferry. | = | Schichallion Quartzite. |
| The Glengarrisdale boulder bed. | = | Schichallion Boulder Bed. |
| The Jura Quartzite. | = | Cammoch Hill Quartzite. |
| Black graphitic schist (Jura Slate). | } | Ben Lawers Schist. |
| Lustrous mica-schists of the S. end of the island. | } | |

*Conclusions on the Jura-Islay Problem.*

1. That the succession in eastern Islay and Jura is the normal Dalradian sequence from lustrous mica-schists, representing the Ben Lawers Schists, through schistose-grit and schistose quartzite of the horizon of the Cammoch Hill Quartzite, to the crumpled black schist with interbedded limestones which correspond to the

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Blair Atholl Schists and Limestones. Then follows an unconformity, with a boulder bed and conglomerate, containing fragments of the underlying limestones, quartzites and schistose grits; this band represents the Schicallion Boulder Bed and it is covered in Islay and northern Jura flaggy and pipe-quartzites, by a fine-grained white quartzite, and dolomites containing fossiloid impressions, and a series of quartzitic sandstones; these rocks correspond to the Ardnoe beds of Crinan, and are Upper Dalradian.

2. The Portaskaig Conglomerate is less altered than the boulder bed in the Schichallion district, as there it was probably more deeply bedded and suffered more thermal metamorphism. The unconformity of the Portaskaig Conglomerate on the Islay Limestone, black schist and Jura Quartzite, seems to me established (*a*) by superposition as regards the limestone at Cleit na Baintighearn and at Losset, and on the Jura Quartzite, at Ben Bhan; (*b*) by its occurrence in a chain of isolated localties across the island from near the Mull of Oa to Portaskaig; and (*c*) by the presence in the conglomerate of pebbles of the limestone, black schist and Jura Quartzite.

3. The Survey map appears to be correct in its representation of the northwestern margin of the quartzite belt from the Mull of Oa through Ben Bhan and Ben Bheigeir; but the features which have led to the claim that the quartzite is unconformable on the slate and black schist are due to an overlap of the quartzites of northern Islay against the Jura Quartzite.

4. The Maol an Fhithich Quartzite is the lower quartzite of the series in northern Islay.

5. The green schistose grits in the northern parts of the Rinns differ essentially from the Torridonian, and are probably Lower Dalradian, in which they agree most nearly with the Loch Lomond Series.

6. The Bowmore Grits agree in character with the quartzites of the Portaskaig Beds, and their characters are Upper Dalradian rather than Torridonian.

7. The complication of the Islay sequence is due to pressure from the south having inverted the rocks of southern Islay and having produced a reverse fault where the Jura Quartzite pressed against the more yielding Islay Limestone and Black Schist and against the overlying conglomerate and sandstone of the northern front of Ben Bhan.



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No. XVII.—SCOTTISH CARBONIFEROUS STRATIGRAPHY: AN INTRODUCTION TO THE STUDY OF THE CARBONIFEROUS ROCKS OF SCOTLAND. By M. MACGREGOR, M.A., B.Sc.

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## I. INTRODUCTION.

THE writer has frequently been asked by students of geology for a reference to any publication containing a recent comparative

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account of Scottish Carboniferous stratigraphy. In the following paper an attempt has been made to supply such an account, to review the sources and present state of our knowledge of the Carboniferous rocks of Scotland, and to indicate the lines along which further research is required. The paper is intended primarily for the use of students of geology who may desire an introduction to the study of a subject which has already gathered round it a voluminous but scattered literature. Certain portions of it, however, especially the section on the correlation of the coals and the tables of comparative vertical sections, will prove, it is hoped, of interest and value to the mining community.[1]

The sources of our information on the subject are as follows:—

(1) Natural sections, such as are exposed on the coast or along rivers; and artificial exposures of strata, such as are seen in quarries or railway-cuttings.

(2) Underground sections provided by borings, shafts, workings, and cross-cut mines.

(3) The published records and descriptions of earlier workers.

Of natural sections, coastal and river, we have a very considerable number. There is, for example, the splendid series of sections along the Fifeshire coast from Charlestown to Anstruther, and indeed as far north as St. Andrews. On the south side of the Firth of Forth there are the shore sections between Bo'ness and Queensferry, and at Granton, Joppa, North Berwick, and Dunbar, as well as the fine inland exposures along the ravines of the Leith Water, the Bilston Burn, North Esk and South Esk. Farther west, there are the gorges of the middle Clyde and of its tributaries the Nethan, Avon, Garrion, Rotten Calder, North Calder and Kelvin. In North Ayrshire we have coastal sections at Ardrossan and near Ayr, and excellent exposures in many streams such as the Lugton, Dusk, Crawfurdland and Kilmarnock Waters. These are quoted merely as examples; and in addition we have numerous other partial but instructive sections which we can go to and study. We could by piecing these carefully together obtain a fairly complete knowledge of the Carboniferous Formation of Scotland and of the lithological and palaeontological characters of each of its main subdivisions, while we would also learn something of the great variations which each of these subdivisions shows. But there would be gaps in our knowledge of local sequences, in

[1] Professor R. W. Dron in his valuable book "The Coalfields of Scotland" (1902; 2nd edition, 1921) has dealt fully, from an economic point of view, with the Carboniferous rocks.

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our knowledge of the variation of individual horizons, and in our knowledge of the detailed structure.

In this difficulty we have recourse to the second source of information referred to. I should like to take the opportunity at this point of acknowledging the debt which geologists owe to the mining community in Scotland. There must be few, if any, areas of Carboniferous rocks that have been so exhaustively explored, or in which the structure and sequence has been so thoroughly made out. The reasons for this are not far to seek. The main coalfields of Scotland are well defined and situated along a comparatively narrow tract of country, while the marked folding and fracturing to which they have been subjected have necessitated abundant preliminary boring and have produced a type of mining characterised by numerous shafts and cross-cut mines. One has merely to glance at a geological map of any part of the Scottish coalfields to realise how each mining area is cut up by the numerous dislocations and intrusions into comparatively small, more or less separate, units. There is a story told of a Scottish mining engineer who was shown on the plans of a large colliery in the English Midlands a ten-foot fault and informed that it "had given a great deal of trouble," but there is no record extant of what he said in reply. Mining for coal, which began as early as the 13th century at least, has been carried on intensively for well over a hundred years. The mining of clayband ironstone may be said to have commenced soon after 1760, and that of blackband about 1828; and the great development of the iron industry during the 19th century led to a continual search for the raw materials it fed on—iron ore, limestone and furnace or splint coal. The oil-shale industry again, which dates from about 1858, has enormously extended our knowledge of a large tract of Carboniferous rocks, while the search for fireclays and refractory materials, and for building-stone, has also added to our fund of information.

Of the records obtained in the early days of mining many are lost and many are so imperfect or so badly localised that they are of little or no use for purposes of present-day research. But in the journals of the numerous borings and shafts of which definite records remain and in the plans of present or abandoned workings (copies of the plans of all abandoned mines have by law been deposited since 1872 at the Home Office) there is a great reservoir of detailed information. The number of bore journals of which copies are filed in the Geological Survey Offices in Edinburgh now exceeds 15,000, but this figure must fall far short of the total number of borings put down. The great majority of these bores

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have been carefully recorded on the six-inch maps, and the journals drawn up in graphic form, with the various coals and index-horizons noted, while wherever opportunity has offered an examination of core-borings has been carried out foot by foot. The borings vary very much in depth, but few exceed 3,000 ft. The deepest boring so far put down in Carboniferous rocks in Scotland is that at Balfour Mains, near Windygates, in Fife, a core-bore sunk, in 1902-7, to a depth of 4,534 feet; the chisel bore drilled in the vain search for oil at West Calder in 1919-21 reached 3,923 feet; while a few recent core-borings for coal have attained depths of almost 3,400 feet. The collection, annotation, indexing and filing of these thousands of journals has been a lengthy task, but we possess in them a series of stratigraphical records invaluable for reference and comparison. By this means we can test the data compiled from incomplete exposures, fill up gaps in the local sequences, study the lateral and vertical variations of sedimentation, follow outcrops, prove the size of faults and the underground extension of igneous rocks, and demonstrate the range of the important intra-Carboniferous unconformities. To this we must add the information derived from underground workings—information regarding the depths of seams, their dip and strike, the direction, inclination and size of faults, the variation in thickness and character of the strata mined, and the occurrence of such phenomena as contemporaneous river-channels.

All this material—boring and mining data alike—has, it should be noted, been voluntarily given to geology by the mining industry. It is their contribution to our joint stock of knowledge. It is true that by the Mining Industry Act of 1926 we have now compulsory notification of, and access to, all borings for minerals over 100 feet in depth. But it is certainly the case that the relations between geologists and those more directly interested in the development of our mineral resources have rested, and still rest, on a basis of mutual co-operation, and the least that we can do in return for the information placed in our hands is to study it as carefully as possible and to apply our knowledge, when required, to any special geological or stratigraphical problems brought to our notice. This friendly co-operation has proved, I think, beneficial to both parties, although our colleagues in the mining world have not always sought our advice in cases where we might have been able to help. They have misread borings, misinterpreted structural features, and even worked seams under the

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wrong name in cases where a careful examination of the associated strata would have shown them the error of their ways. Of more venial mistakes I recall the case of the optimist who doubly dared providence by commencing a boring for coal in Old Red Sandstone rocks on the first of April; the case of the precisian who recorded in the journal of a boring a " vacuum " of two feet; and, at the other end of the scale, that of the genial spirit, unwearied in well-doing, who described volcanic detritus and lavas as " forty fathoms of ironstone." Over the mistakes made by geologists in their turn I shall draw a veil.

The third source of information open to us is furnished by the published accounts of earlier workers. There are, in the first place, the researches of the numerous enthusiastic observers the result of whose labours have appeared in the *Transactions* of scientific societies such as this. To these we are under a great debt of gratitude and no one will cavil if I refer, by way of illustration, to the great services rendered in this connection by such men as Young, Craig, Hunter, Neilson and Macnair in the West of Scotland, or in the East by Bald, Hibbert, Milne-Home, Traquair and Kirkby. Among those who are happily still with us must be mentioned Mr. John Smith of Dalry and Mr. James Wright of Kirkcaldy. In the second place we have the various publications—district and sheet memoirs, economic memoirs, six-inch, one-inch and quarter-inch maps—of the Geological Survey. The primary survey of the Scottish coalfields commenced in 1854, and I should like to express at this point the gratitude which every student of our Carboniferous rocks must feel for the magnificent work accomplished by such pioneers as the two Geikies, Jack, Peach and Gunn. The first revision began in 1902 and has now been completed except for part of Fife and the small outlying fields at Sanquhar, Campbeltown and Canonbie. The number of revised six-inch geological quarter-sheets,[1] each with vertical section attached, so far published is 300 and 23 are in the press.

It must be remembered that these six-inch maps of the coalfields are in themselves studies in detailed stratigraphy and I wish to say something of the difficulties that face the geologist who attempts to produce one. He has, of course, to examine any

[1] The six-inch sheets are numbered and are now issued as four separate quarter-sheets, e.g. Lanark 8 N.W., S.W., N.E., S.E.; each quarter-sheet contains an area of six square miles.

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natural exposures of rock, and note any lithological and palaeontological peculiarities of these, but in many cases the exposures may be so few and partial as to be of very little service. There may be three or four working collieries as well as several abandoned ones and there may possibly be as many as 200 borings that have been put down from time to time within the area covered by one quarter-sheet. The information he requires is scattered over the country, with mining engineers, at colliery offices, with estate agents or in the archives of the Home Office in London, and it has all to be collected and sifted. He may obtain in one place boring records of which the sites are not known and in another place the sites of borings of which the journals have been mislaid or lost, but he accepts them all, hoping that some day his good fortune will throw in his way the sites of the former and the journals of the latter. It is impossible to say where old records, often of no value to their present owner but of the greatest use for purposes of detailed mapping, may be hidden away, neglected or forgotten, and the search for them may be long and wearisome. It is only when all this work has been done, the underground data assimilated, the borings and shaft sections drawn up and annotated, and the surface exposures assigned their proper position in the geological sequence, that the making of the map can proceed, and the outcrops of the different beds be accurately laid down. Sooner or later, however, there comes an area where he has no underground information and no borings, and where perhaps nothing is to be seen at the surface but boulder clay. It is then that he resorts to such unsatisfactory subterfuges as "conjectural outcrop," "probable position," and "inferred continuation." And finally when the map is complete and published, sources of information from which he was at first barred may be thrown open to him, fresh evidence may come to light, or new bores be put down; all these mean additions to the map and very often adjustment of boundary lines and of outcrops.

## II. THE CARBONIFEROUS SEDIMENTS: GENERAL ACCOUNT.

### (1) Subdivisions and Variations in Thickness.

The Carboniferous sediments in Scotland, where most fully developed, may attain a thickness of nearly 12,000 feet or more than two miles. The accompanying table shows how the figure has been arrived at:—

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| | Subdivisions | Central Coalfield | | The Lothians | | Fife | |
|---|---|---|---|---|---|---|---|
| | | West | North-East | W. Lothian | Midlothian | West and Central | East |
| | | Feet | Feet | Feet | Feet | Feet | Feet |
| Coal Measures | Barren Red Measures | **960+** | | | 550+ | | *1000+* |
| | Productive Measures | **1220** | | | 1600 | | *1770* |
| Carboniferous Limestone Series | Millstone Grit | **760** | **1125** | | *740* | **1120** | |
| | Upper Limestone Group | **1320** | **1650** | | 1070 | **1440** | |
| | Limestone Coal Group | **1200** | **960** | | 1070 | **1640** | |
| | Lower Limestone Group | **480** | **450** | | *700* | **600** | |
| Calciferous Sandstone Series | Oil-Shale Group — Upper | **1080** (up to) | | **2800** | | | *3800* |
| | Oil-Shale Group — Lower | Clyde Plateau Lavas | | | ?2000 (Arthur's Seat Lavas) | | |
| | Cementstone Group | *700+* | | | *600+* | | *?500* |
| | Thickness of sediments | 7720+ | | 11,130+ | | 11,880+ | |

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In regard to this table the following points should be noted:—

(1) The figures represent approximately the *maximum* known thickness for the main subdivisions in the various districts indicated. Those in heavy type (Clarendon) are taken from borings or shaft sections; those in lighter type (Roman) are based partly on mining evidence (borings, sections in cross-cut mines), partly on natural sections; those in italics are based wholly or mainly on natural sections.

(2) Figures followed by a + sign indicate that the full thickness is not known. Thus the Barren Red Measures at the top of the succession are incompletely preserved, while the Calciferous Sandstone Series in the West of Scotland is largely, and sometimes almost entirely, replaced by contemporaneous volcanic rocks. These volcanic rocks are estimated to be between 2,000 and 3,000 feet thick locally, and must at one time have been considerably thicker, for there is clear evidence that they were subjected after extrusion to subaerial denudation. The accumulation and subsequent partial erosion of this pile of volcanic material clearly represents a prolonged interval of time, during which nearly the whole of the Oil-Shale Group of the Lothians—over 4,000 ft. thick—was deposited. In the latter area again continuity of deposition throughout Calciferous Sandstone times was interrupted by the volcanic episode which produced the lavas of Arthur's Seat and the Calton Hill, of Corston Hill (Sheet 32),[1] and of the country around Carnwath (Sheets 23, 24).

(3) All the subdivisions show considerable variation in thickness in each district. Thus in the Central Coalfield the Productive Coal Measures vary from 816 to 1,220 ft., the Lower Limestone Group is locally only 104 ft. thick, while the Millstone Grit, which at its maximum is approximately 1,125 ft., is represented in one section by only 8 ft. of sandstone (*see* p. 462).

The Carboniferous sequence in Ayrshire is notably thinner than in the Central Coalfield, Midlothian, or Fife. In the northern part of the county (Sheet 22) the figures for maximum thickness assigned to the subdivisions are:—

| | | Ft. |
|---|---|---|
| Barren Red Measures .. .. .. | | 300+ |
| Productive Measures .. .. | approximately | 700 |

[1] This and similar references throughout the paper are to the Sheets of the One-inch Geological Survey map of Scotland; *see* coloured map.

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| | Ft. |
|---|---|
| Millstone Grit (mostly lavas) .. .. | 50 to 540 |
| Upper Limestone Group .. | possibly up to 360 |
| Limestone Coal Group .. .. .. | 650 |
| Lower Limestone Group .. .. .. | 120 |
| Upper Calciferous Sandstone .. | up to about 200 |
| [Clyde Plateau Lavas] | |
| | 2,870 |

The thickness of the Clyde Plateau lava group in the Beith Hills is estimated as at least 1,000 ft., but is probably much more than this in the country lying to the east and north (Renfrewshire Uplands and Ayrshire-Renfrewshire watershed). Here again the Upper Calciferous Sandstone sediments rest unconformably and with a marked overlap on the lavas, and are separated from them by a basal layer, 2 to 50 ft. thick, of volcanic detritus. The volcanic rocks thin away rapidly towards Ardrossan; south of the Irvine Valley they are either entirely absent or represented by a few thin flows, and the Calciferous Sandstone Series consists, where best developed, of 400 to 500 ft. of strata belonging mainly to the Cementstone group. As in the Central Coalfield all the groups show marked variations in thickness. Thus the Limestone Coal Group, which at Kilbirnie is about 650 ft. and at Dalry about 620 ft., is reduced in the southern part of the Sheet to about 50 ft., while the Upper Limestone Group shows a similar diminution from about 360 ft. in the north to as little as 25 ft. 4 miles south of Kilmarnock. The Millstone Grit in North Ayrshire is largely composed of volcanic rocks which attain a maximum thickness of about 540 ft. in the neighbourhood of Gailes. The Productive Coal Measures of North Ayrshire vary from about 500 to about 700 ft. but only about 300 ft. of the Barren Red Measures have been preserved. Farther south again in Central Ayrshire where the Carboniferous rocks are overlain by the New Red Sandstone (? Permian) lavas the figures are:—

| | |
|---|---|
| Barren Red Measures: maximum known thickness | 1776 ft. |
| Productive Coal Measures about .. .. | 900 ft. |

There is probably an unconformity at the base of the lavas, however, and part of the Barren Red Measures may be wanting.

The approximate figures for South Ayrshire are:—

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| | Ft. |
|---|---|
| Barren Red Measures .. .. .. .. | 1,000+ |
| Productive Coal Measures .. .. .. | 1,300 |
| Millstone Grit .. .. .. .. .. | 540 |
| Upper Limestone Group .. .. .. | 780 |
| Limestone Coal Group .. .. .. .. | 350 |
| Lower Limestone Group.. .. .. .. | 120 |
| Calciferous Sandstone Series, possibly .. | 650 |
| | 4,740 |

The marked attenuation that affects the Carboniferous sediments as they are followed from Fife into Ayrshire may be illustrated by setting down in tabular form the combined thickness of the Productive Coal Measures, Millstone Grit, and Carboniferous Limestone Series for the different districts:—

| | |
|---|---|
| Fife .. .. .. .. .. .. | 6580 |
| Midlothian .. .. .. .. .. | 5180 |
| Central Coalfield .. .. .. .. .. | 4980 |
| North Ayrshire .. .. .. .. .. | 2370 |
| South Ayrshire .. .. .. .. .. | 3090[1] |

The variations in thickness shown by the various subdivisions of the Scottish Carboniferous are due in the main to attenuation of the sediments and not to non-deposition or overlap. The Carboniferous Limestone Series, for example, may reach a thickness of 3600 in parts of Fife, but on the south side of the Central Coalfield it is reduced to about 700 ft. and in parts of Ayrshire may be only 100 ft. thick. The attenuation affects each of its subdivisions and when the variations are examined in detail they appear to indicate differential crustal movements over the area of deposition, producing relatively stable and unstable areas. The breaking up of the old land masses composed of Calciferous Sandstone lavas and older rocks towards the close of Calciferous Sandstone times would appear to have been brought about by the formation of gulfs in which the area of sedimentation was gradually extended. The higher Calciferous Sandstone sediments

[1] In Arran the Carboniferous Limestone Series was estimated by Gunn to be 750 ft. thick at Laggan, decreasing to 425 ft. at Corrie; *see* 'Geology of North Arran, etc.,' *Mem. Geol. Surv.*, 1903, p. 46; 'Geology of Arran,' *Mem. Geol. Surv.*, 1928, p. 48.

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overlapped on to the old land areas[1] and then followed the general subsidence which carried the greater part of the region beneath the waters of the sea (the Hurlet transgression; *see* p. 499). This subsidence was not uniform, however, and the land barriers which separated the basins and gulfs of late Calciferous Sandstone times persisted throughout Carboniferous Limestone times as relatively more stable areas over which sedimentation was less. Differential subsidence and consequent variation in the amount of sediment seems to have taken place over the whole region of deposition. Locally land areas persisted throughout Lower Limestone Group, and even into Limestone Coal Group, times.

In the Douglas Valley basin (Sheet 23) the Carboniferous sediments, including at least 700 feet of Barren Red Measures, cannot be much less than 5000 feet thick. In the South of Scotland again, in the Eskdale-Liddisdale country, Peach and Horne[2] have estimated the Carboniferous rocks as approximately 8000 to 8400 feet thick. Their figures are:—

| | | Thickness in Ft. |
|---|---|---|
| | Liddisdale Sequence | |
| Coal Measures. | Coal Measures { Upper, Middle, Lower } | about 3000 |
| Millstone Grit. | Millstone Grit. | 670 |
| Carboniferous Limestone Series | Upper Limestones. | 300 to 400 |
| | Kilnholm Coal Group. | 350 |
| | Lower Limestones. | 500 to 700 |
| Oil-Shale Group | Lawston Linn and Lewis Burn Coals | 400 to 500 |
| | Glencartholm Volcanic Group | about 300 |
| | Fell Sandstone Group. | 400 to 600 |
| Cementstone Group | Cementstone Group (with marine limestones). | 1200 to 1500 |
| | Whita Sandstone; where best developed, about | 700 |
| | Birrenswark Volcanic Group | |

[1] They rest, for example, not only on Calciferous Sandstone lavas, but also, in places, on the Cementstone Group or on the Upper Old Red Sandstone.

[2] 'The Canonbie Coalfield,' *Trans. Roy. Soc. Edinb.*, vol. xl, part 4, 1903, p. 839.

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The length of time needed for the accumulation of this pile of materials may be gauged by the actual thickness—locally, as we have seen, over 11,800 feet—of the rocks; it may be gauged by the fact that it represents the period between the two great epicontinental formations of the Old and the New Red Sandstone; or it may be gauged by the evidence for prolonged volcanic episodes (*see* Figure 4), for intraformational unconformities and for palaeontological 'breaks.' It is borne witness to also by the very nature of the sediments themselves; much the greater part of the Scottish Carboniferous consists essentially of shallow-water deposits, laid down, no doubt comparatively rapidly, over a slowly subsiding area, but the marked alternation of beds of distinct lithological types suggests that the time occupied by deposition was only a fraction of the whole. Sedimentary cycles recur again and again throughout the succession, indicating the subsidence of an old land surface beneath the waters of a shallow sea, and the gradual shoaling of the latter subsequently with detrital material. Sometimes the cycle is broken or incomplete, and in the Coal Measures and Limestone Coal Group there are few evidences of marine conditions. These recurrent cycles testify to slowly changing geographical conditions throughout a very long period of time. Among the Scottish Carboniferous sediments there are river deposits, deposits laid down as deltas and sand-bars, deposits formed in lagoons and estuaries, deposits accumulated on the land, along shores, in shallow water, or in the open sea. Amid this varied lithological assemblage the stratigrapher has to walk warily and may easily lose his way.

### (2) General Succession and Principal Index Horizons.

I have been sometimes asked to draw up in tabular or graphic form a general statement of the Scottish Carboniferous succession, showing the principal index-beds and the main economic horizons set out in proper geological sequence. It would be impossible, as we shall see later, to carry out that task in the detail suggested. I have, however, prepared the following diagram to show the main subdivisions and the more important horizons that are made use of for comparative stratigraphical purposes over wide areas (Fig. 1). This diagram, with a few supplementary notes, will serve as a basis for a more detailed study.

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# DIAGRAM TO SHOW
# GENERAL SUCCESSION IN
# Carboniferous Rocks of Central Scotland
## With Subdivisions & Principal Index Horizons.

***The probable equivalents south of the Silurian Tableland are indicated on the right.***

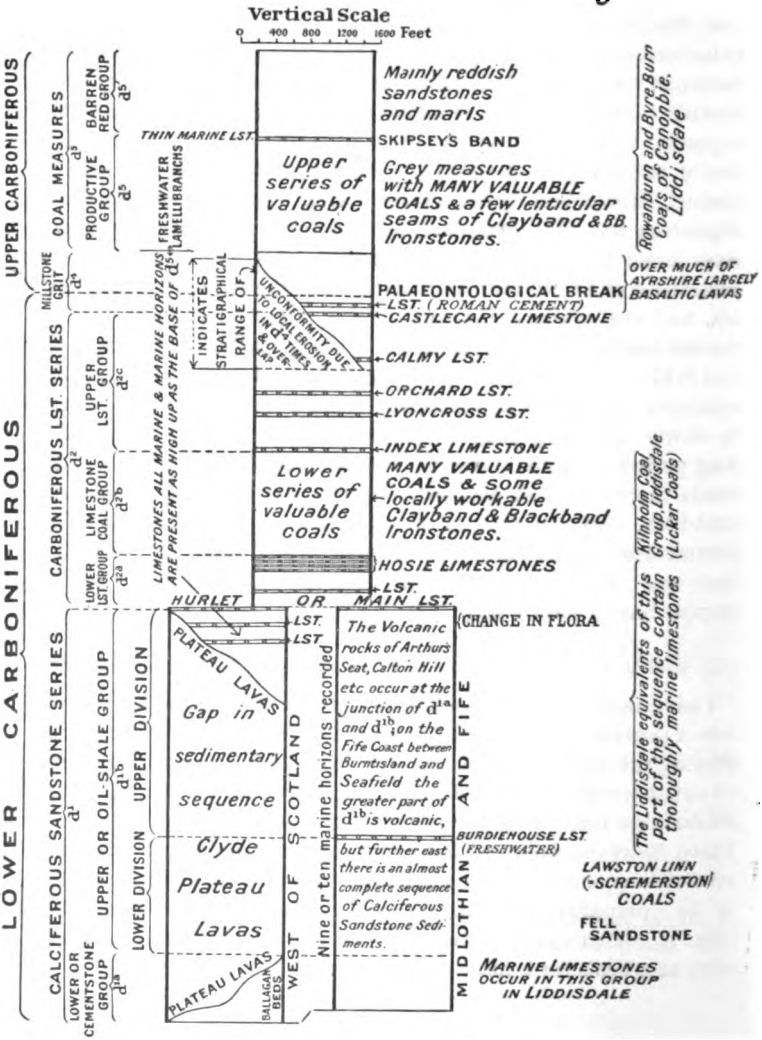
Vertical Scale
0 400 800 1200 1600 Feet
UPPER CARBONIFEROUS
LOWER CARBONIFEROUS
COAL MEASURES
CARBONIFEROUS LST. SERIES
CALCIFEROUS SANDSTONE SERIES
MILLSTONE GRIT
PRODUCTIVE GROUP
BARREN RED GROUP
UPPER LST. GROUP
LIMESTONE COAL GROUP
LOWER LST. GROUP
UPPER OR OIL-SHALE GROUP
LOWER OR CEMENTSTONE GROUP
UPPER DIVISION
LOWER DIVISION
THIN MARINE LST.
FRESHWATER LAMELLIBRANCHS
INDICATES STRATIGRAPHICAL RANGE OF
UNCONFORMITY DUE TO LOCAL EROSION IN CAL-TIMES & OVER-LAP
LIMESTONES ALL MARINE & MARINE HORIZONS ARE PRESENT AS HIGH UP AS THE BASE OF d2c
HURLET
OR
MAIN LST.
LST.
LST.
PLATEAU LAVAS
Gap in sedimentary sequence
Clyde Plateau Lavas
PLATEAU LAVAS
BALLAGAN BEDS
WEST OF SCOTLAND
Nine or ten marine horizons recorded
MIDLOTHIAN AND FIFE
Mainly reddish sandstones and marls
SKIPSEY'S BAND
Grey measures with MANY VALUABLE COALS & a few lenticular seams of Clayband & BB. Ironstones.
PALAEONTOLOGICAL BREAK
LST. (ROMAN CEMENT)
CASTLECARY LIMESTONE
CALMY LST.
ORCHARD LST.
LYONCROSS LST.
INDEX LIMESTONE
Lower series of valuable coals
MANY VALUABLE COALS & some locally workable Clayband & Blackband Ironstones.
HOSIE LIMESTONES
LST.
CHANGE IN FLORA
The Volcanic rocks of Arthurs Seat, Calton Hill etc occur at the junction of d1a and d1b; on the Fife Coast between Burntisland and Seafield the greater part of d1b is volcanic,
but further east there is an almost complete sequence of Calciferous Sandstone Sediments.
BURDIEHOUSE LST. (FRESHWATER)
LAWSTON LINN (=SCREMERSTON) COALS
FELL SANDSTONE
MARINE LIMESTONES OCCUR IN THIS GROUP IN LIDDISDALE
Rowanburn and Byre Burn Coals of Canonbie. Liddisdale
OVER MUCH OF AYRSHIRE LARGELY BASALTIC LAVAS
Kilnholm Coal Group. Liddisdale (Licker Coals)
The Liddisdale equivalents of this part of the sequence contain thoroughly marine limestones

FIG. 1.

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The names given to the various index-beds in the above diagram are those that are best known and most widely made use of, but it should be remembered that each of them passes under a variety of local designations. This is, of course, due to the fact that local sequences were first established while correlations between different areas by means of lithological and faunal criteria were only slowly worked out. Considerable difficulty and confusion has arisen from the multiplicity of names in use for the different index-horizons, and the confusion is worse, as we shall see later, in the case of the nomenclature of the coals and ironstones. Thus, the Hurlet or Main Limestone, at the base of the Carboniferous Limestone Series in the country south-west of Glasgow (Sheet 30), is correlated with the Cobbinshaw of Tarbrax (Sheets 32, 24), the West Kirkton of Bathgate (Sheet 31), the Murrayshall of Stirling (Sheet 39), the Station of Charlestown (Sheet 32), the Dockra of North Ayrshire (Sheet 22), the Hawthorn of Muirkirk (Sheets 23, 15), the Captain's Bridge or Patna Limestone of South Ayrshire (Sheet 14), the Corrie Limestone of Arran (Sheet 21), etc.

The Hosie Limestones, three or four in number, pass under various local designations in the different districts or even within the same district; the Top Hosie is known as the Calderwood Cement at East Kilbride, as the Lingula Limestone at Carluke (Sheet 23), as the Top McDonald at Muirkirk (Sheet 15), etc. The Index Limestone is known sometimes as the Seven Foot in the Muirkirk district, and as the Highfield in North Ayrshire. The Calmy Limestone again passes under at least six other names in different parts of the Central Coalfield; Arden (Sheet 30), Gair (Sheet 23), Robroyston, Hirst, Shirva and Dykeneuk (Sheet 31), and is correlated with the Upper Linn or Linn Spout of North Ayrshire (Sheet 22), the Gill Limestone of Douglas (Sheet 23), the Blue Tour of Muirkirk, etc. Sometimes again the limestones are numbered or lettered; thus in the Midlothian sequence the Index is No. 4 Limestone, the Calmy is No 5, and the Castlecary or Levenseat is No. 6.[1] These are quoted as examples of the somewhat perplexing nomenclature with which the student of our Carboniferous rocks is faced. Many of the names originally essential in working out local sequences have already been discarded, but in striving after a standard nomenclature it should not be forgotten that the more local names recur again and again in the earlier literature of the subject. In dealing with a limestone

[1] *See also* pp. 519, 528.

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sequence nowadays therefore it is advisable to retain the local name as an alternative; thus the Calmy Limestone of the country south-west of Glasgow would be called the Calmy or Arden, and the same limestone in the Linlithgow district referred to as the Calmy or Dykeneuk.

The horizons made use of as boundaries for the subdivisions of the Scottish Carboniferous need only be briefly referred to. Skipsey's Marine Band, taken as the top of the Productive Coal Measures, is characteristically a dark earthy limestone, one to two feet thick, and occurs as such in the Motherwell, Wishaw and Hamilton areas (Central Coalfield, Sheets 31, 23) in the Douglas Valley coalfield (Sheet 23), at Sanquhar (Sheet 15) and at New Cumnock, Patna and Dalmellington in Ayrshire (Sheet 14).[1] The first occurrence of marine fossils at this horizon was that recorded by Skipsey in 1865 from material obtained in a pit-sinking at Drumpark, near Baillieston, a little south-west of Coatbridge (Sheet 31); according to his account[2] the marine fossils were obtained from a thin bed of purplish shales. Marine bands (shales with calcareous nodules or lenticles) are also taken in Fife[3] and Midlothian[4] as the boundary between Productive Coal Measures and Barren Red Measures. In each district the band indicates the sudden incursion of a marine fauna into an area where estuarine conditions of deposition had been long established, and although our records are as yet few and scattered there is no reason to doubt the stratigraphical equivalence of the marine horizons referred to. Skipsey's Marine Band, as we shall see, is in all probability the equivalent of the well-known Mansfield Marine Bed and its representatives in the English and Welsh coalfields (p. 484). The base of the Productive Measures again is drawn in each of the main coalfields where the barren arenaceous

[1] *See* J. Smith and C. T. Clough, 'The Marine Beds near the Base of the Upper Carboniferous Red Barren Measures of Scotland,' in 'Summary of Progress for 1907,' 1908, p. 127; 'Econ. Geol. Central Coalfield, Area V,' 1926 p. 85; do. Area VII, 1920, p. 100; also 'Summary of Progress for 1924,' p. 94; all *Mem. Geol. Surv.*

[2] R. W. Skipsey, 'On the Occurrence of Carboniferous Limestone Fossils in the Upper Coal Measures to the East of Glasgow,' *Trans. Geol. Soc., Glasgow*, vol. ii, part i, 1865, p. 52.

[3] *See* 'Geology of Central and Western Fife,' *Mem. Geol. Surv.*, 1900, p. 147.

[4] *See* 'Geology of Neighbourhood of Edinburgh,' *Mem. Geol. Surv.*, 1910, p. 272.

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strata of the Millstone Grit pass upwards into the more varied carbonaceous sediments of the higher series. The change takes place in the Central Coalfield at or about the position of the Upper or Crofthead Slatyband (*see* Fig. 6)[1] which has accordingly been taken as defining the boundary for this district; although a very local deposit, its position over the greater part of the coalfield can be very accurately determined by close comparison of the numerous boring sections available. In North Ayrshire the boundary is drawn at the top of the Millstone Grit volcanic series,[2] and in South-Central and South Ayrshire, where the lavas are absent, at the horizon of the well-known Lugar, Dalmellington or Burnfoot Blackband; this change of datum has, however, very little stratigraphical significance and the base of the Coal Measures throughout Ayrshire may be regarded as taken at approximately the same level. In Midlothian and in Fife again the boundary line is drawn at the top of the thick coarse sandstones of the Millstone Grit. Thus, in each of the main coalfields, it is a more or less arbitrary line, but there is no reason to doubt the *general* stratigraphical equivalence of the boundaries selected. It should be noted, however, that they indicate in each case a change in conditions of sedimentation, and the change may possibly have begun earlier in one district than in another. There is some evidence, for example, to show that the period of formation of thick coals commenced rather earlier in the north-east (*see* p. 539). The Castlecary or Levenseat Limestone is the first important limestone below the sandstones of the Millstone Grit and has accordingly been adopted as the top of the Carboniferous Limestone Series; in areas where it is absent, as over much of the south-west of the Central Coalfield and North Ayrshire (p. 462), an arbitrary line has to be taken. There is no need to stress the importance of the Index Limestone; it is a very persistent and constant datum-line over the greater part of the Scottish Coalfields and forms the ' index ' or ' key ' horizon to the valuable Limestone Coals below; it may, however, be cut out in certain areas by a slight local unconformity and in Fife is very

[1] Slatyband is the term used in Scotland for an ironstone showing alternating clayband and blackband laminae. The Crofthead Slatyband, as a workable ironstone, was confined to a small area near Fauldhouse (Sheet 31).

[2] The top of the Series is defined by the Ayrshire Bauxitic Clay, a residual deposit formed as a result of prolonged weathering and decomposition of the lavas.



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often represented only by a thin band of fossiliferous shales. Similarly, the shales above the Top Hosie Limestone mark the base of the Limestone Coal Group, though so far as valuable coals are concerned it might just as well be drawn at the higher horizon of the Johnstone Shell Bed. The Hurlet and Top Hosie Limestones indicate the beginning and end of Lower Limestone Group times and are both traceable (though under different names) throughout the coalfields. The Hurlet Seam also ushers in a new epoch in Scottish Carboniferous history, when most of the old land-barriers of Calciferous Sandstone times were submerged beneath the sea.

## III. PALAEONTOLOGICAL SUBDIVISIONS.

The various subdivisions into which the Scottish Carboniferous Rocks are divided are essentially lithological; their very names—Barren Red Measures, Productive Coal Measures, Carboniferous Limestone Series, etc.—are clearly expressive of their different sedimentary content. But before dealing in detail with these from the point of view of lithology I wish to say something of the palaeontological subdivisions and of the floral and faunal evidence on which these are based.

### (1) Lower and Upper Carboniferous.

The researches of Kidston[1] and Traquair[2] on the fossil plants and fishes led them to the conclusion that a marked palaeontological break occurred within the Millstone Grit Series. The Carboniferous rocks are accordingly divided palaeontologically into Lower and Upper Carboniferous.

Upper { Coal Measures { Barren Red Measures. / Productive Measures. / Millstone Grit, upper two thirds.

[1] R. Kidston 'On the Various Divisions of British Carboniferous Rocks as determined by their Fossil Flora,' *Proc. Roy. Phys. Soc. Edinb.*, vol. xii, 1894, pp. 183-257. 'On the Divisions and Correlation of the Upper Portion of the Coal Measures,' *Quart. Journ. Geol. Soc.*, vol. lxi, 1905, pp. 308-321. 'Fossil Plants of the Carboniferous Rocks of Great Britain,' Part i, *Mem. Geol. Surv.*, 1923, pp. 8, 9, 13.

[2] R. H. Traquair, 'Fossil Dipnoi and Ganoidei of Fife and the Lothians,' *Proc. Roy. Soc. Edinb.*, vol. xvii, 1891, pp. 384-400. 'On the Distribution of Fossil Fish-remains in the Carboniferous Rocks of the Edinburgh District,' *Trans. Roy. Soc. Edinb.*, 1903., vol. xl, pp, 687-707; and other papers.

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| | | |
|---|---|---|
| Lower | Millstone Grit, lower part. | |
| | Carboniferous Limestone Series. | Upper Limestone Group. |
| | | Limestone Coal Group. |
| | | Lower Limestone Group. |
| | Calciferous Sandstone Series. | Oil-Shale Group. |
| | | Cementstone Group. |

The plants obtained from above the ' break ' are specifically distinct from those found below it, with one or two exceptions. Thus *Lepidodendron veltheimianum* Sternb., a very characteristic Lower Carboniferous species, has a range which includes the lowest beds of the Upper Carboniferous, while there is one Upper Carboniferous species which is closely related to, if not specifically identical with, a Limestone Coal Group form. Similarly the *estuarine* fish fauna of the Lower Carboniferous rocks is replaced above the ' break ' by a new assemblage " from which nearly all the Lower Carboniferous species, and with them also a number of genera, have disappeared." The data furnished by the invertebrate fauna are not so conclusive, but the evidence of the gasterpods and marine lamellibranchs[1] points to a marked faunal change soon after the close of Upper Limestone Group times. A number of species (e.g. *Prothyris elegans* Meek.), obtained from the lower part of the Millstone Grit, were regarded by Wheelton Hind as identical with forms found in the Coal Measures of Nebraska and Illinois (' Nebraskan Fauna '); many of these again have been recorded from Russia in rocks referred to a late stage of Carboniferous times. The brachiopods found at certain horizons in the lower part of the Millstone Grit appear to have Upper Carboniferous affinities, or at least to suggest a post-Visean age (e.g. *Productus carbonarius* de Kon., *Productus* cf. *cora* d'Orb and *Meekella leei*), although in the case of this group there is evidence that the faunal modification had begun at a somewhat earlier date. *Meekella*, for example, is recorded from the Upper Limestones of N. Ayrshire. The giganteid *Producti* again do not extend, so far as is known, into the higher beds of the Carboniferous Limestone Series and accordingly the dividing line would in this case be drawn some little distance below the Castlecary Limestone.[2] The difference in the stratigraphical positions of the

[1] *See* Wheelton Hind, ' On the Lamellibranch and Gasteropod Fauna found in the Millstone Grit of Scotland,' *Trans. Roy. Soc. Edinb.*, 1908, vol. xlvi, 1909, pp. 331-359.

[2] *See* G. W. Lee in ' Geology of the Glasgow District,' *Mem. Geol. Surv.*, 1925, p. 133.

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'break' is not, however, great. On the evidence of the goniatite fauna Bisat[1] correlates the lower part of the Scottish Millstone Grit with the Upper E (*Bisulcatum* zone) or Lower H (*Diadema* zone) of his Lancastrian succession and the occurrence of *Tylonautilus nodiferus* (*Nautilus nodiferus* of Armstrong)[2] in North England in association with goniates indicating a level just below the *Bisulcatum* zone, and in Scotland in beds that include the Calmy and Castlecary limestones immensely strengthens this correlation.[3] Bisat adopted the base of E as the division between his Upper and Lower goniatite faunas, but later work indicates that the dividing line should be drawn at a somewhat higher level, between E and H. It is at or near this level in Bisat's Lancastrian that the great floral 'break' occurs.

The significance of the palaeontological 'break' in Scotland is a question of considerable difficulty. Traquair,[4] after commenting upon the replacement of the Lower Carboniferous fish fauna by an Upper Carboniferous assemblage, says: "Why this sweeping change took place about the time of the Millstone Grit we do not know." Kidston,[5] in summarising the results of his work in Scotland and Staffordshire as regards the floral 'break,' remarks: "The sudden disappearance of one flora and the equally sudden appearance of another is one of the most remarkable facts in Vegetable Palaeontology, and one for which I can offer no satisfactory explanation. The fact that the deposits composing the 'Millstone Grit' in which the plant beds occur are similar in nature in both these botanical provinces, shows that there can have been little change in the physical conditions which maintained at the time of their deposition." He also remarks on the absence of any definite evidence of an unconformity. Peach[6]

[1] W. S. Bisat, 'The Carboniferous Goniatites of the North of England and their Zones,' *Proc. Yorks. Geol. Soc.*, vol. xx, part i, 1924, p. 16.

[2] J. Armstrong, 'Description of two new species of shells from the Carboniferous Limestone of Clydesdale.' *Trans. Geol. Soc. Glasg.*, vol. ii, part 1, 1865, pp. 74-75 and Plate 1.

[3] J. Pringle and J. W. Jackson, '*Tylonautilus nodiferus* gen. nov.: A Carboniferous Guide Fossil,' *Naturalist*, Dec., 1928.

[4] *Trans. Roy. Soc. Edinb.*, 1903, vol. xl, p. 707.

[5] 'Fossil Plants of the Carboniferous Rocks of Great Britain,' Part 1, *Mem. Geol. Surv.*, 1923, p. 11.

[6] 'Some Points in the Natural History of the Carboniferous Period in East Scotland,' *Proc. Roy. Phys. Soc. Edinb.*, 1916, vol. xix, p. 257.

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again, in his study of the Carboniferous of the East of Scotland pointed out that " as the rocks afford no sign of physical break in the region under consideration, some great physical change must have taken place outside it, to account for this almost complete replacement of the flora and fish fauna by others. Change of climate alone seems powerless to bring about so sudden a revulsion." It is not clear how far the floral ' break,' demonstrated by Kidston for Scotland and North Staffordshire, extends. There is no evidence, for example, for a parallel phenomenon in the Carboniferous of Belgium or Silesia, and Prof. E. B. Bailey[1] has advanced a convincing explanation for the contrast between the two regions. He suggests " that temporary marine isolations induced a difference in the Carboniferous floral history of the two regions until the spreading deltas of the Millstone Grit provided a highway for plant migration. According to this proposition the plant-break of the Scottish Carboniferous is due to a replacement of the local flora by a southern competitor."

The Millstone Grit must be considered as in the main built up of deltaic deposits, the material being derived from an old land area lying to the north. The final shoaling of the Carboniferous Limestone sea, and the replacement of the more or less marine sediments of the Upper Limestone Group by the deltaic deposits of the Millstone Grit represent in themselves very considerable physiographic changes. We have in addition clear evidence that portions of the Scottish area were uplifted during part of Millstone Grit times and subjected to denudation. An instance of this has been very carefully worked out in detail by Mr. C. H. Dinham[2] in the Larkhall district. Along the south side of the Central Coalfield—especially near Larkhall and Stonehouse—there is the clearest evidence for unconformity within the Millstone Grit; nearly the whole of the Series, as well as part of the Upper Limestone Group, is locally absent through erosion in Millstone Grit times accompanied by overlap. In one of the natural sections in the River Avon the following sequence can be established:—

[1] ' Plant Migration across the Millstone Grit,' *Geol. Mag.*, vol. lxiii, 1926, p. 49.

[2] ' Econ. Geol. Central Coalfield, Area IX,' *Mem. Geol. Surv.*, 1921, pp. 76-79. *See also* M. Macgregor, *ibid.*, p. 72, and in ' Area VI,' 1923, pp. 66, 73. Much of the information is presented in the published six-inch sheets of the Larkhall district (Lanark 17 S.E., 18 S.W., 24 N.W. *especially*).

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Base of Coal Measures.

| | |
|---|---|
| Millstone Grit | Sandy fireclay, 1½ ft. |
| | Sandstone, varying from 8 to 24 ft. |

(Line of Erosion).

| | |
|---|---|
| Upper Limestone Group (part of). | Shales, 13 ft. |
| | Shales, with thin limestone ribs, 14 ft. |
| | Calmy Limestone, 3 ft. |

Borings indicate that locally the Calmy Limestone itself is missing owing to erosion. The absence of the Castlecary Limestone again over large areas in the central and southern parts of the coalfield is also ascribed to local erosion in early Millstone Grit times of the Castlecary beds and to their replacement by coarse arenaceous sediments. A similar phenomenon has been demonstrated in North Ayrshire[1] (where the Millstone Grit consists largely of basaltic lavas poured out in successive flows over a low-lying and slowly-sinking area) and possibly occurs also in the Kinglassie district of Fife.[2] A slight unconformity has also been noted near the base of the Millstone Grit in South Ayrshire (Dunaskin Glen)[3] while its equivalent in the Midlothian Basin (Roslin Sandstone Series) shows a number of conglomeratic bands, about 3 ft. thick, with indications of local erosion at their base.

It is of interest to note in this connection that there is evidence in certain areas pointing to a more marked overlap of the Millstone Grit on to lower members of the Carboniferous succession.

(1) On the southern and south-eastern margin of the Douglas Valley coalfield (north margin of Sheet 15, south margin of Sheet 23) the evidence obtained from certain natural sections and borings suggests that the Millstone Grit overlaps the Upper Limestone and Limestone Coal Groups in turn and comes to rest almost directly on the Main or Hawthorn Limestone, the basal member of the Lower Limestone Group. In the Kennox Water, for example, in Sheet 15, Millstone Grit strata overlie the Upper Limestone Group with apparent conformity, but in the Glentaggart Burn, 1½ miles to the east, there is no evidence of the occurrence either of the Upper Limestone Group or of the Limestone Coal Group, and Millstone Grit strata come on in force a short

[1] 'Geology of North Ayrshire,' *Mem. Geol. Surv.*, 1930, p. 197.

[2] The Castlecary Limestone is not present here and the highest limestone in the Upper Limestone Group is identified with the Calmy. *See* 'Summary of Progress for 1927,' *Mem. Geol. Surv.*, 1928, p. 65.

[3] 'Summary of Progress for 1925,' *Mem. Geol. Surv.*, 1926, p. 97.

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distance downstream from the Main (or Hawthorn) Limestone. In the upper part of the Townhead Burn again (Sheet 23; east side of Douglas basin) a series of barren sandstones have been referred tentatively to the Millstone Grit, and borings show that these rest unconformably (with conglomeratic bands near the base) on a thin development of Lower Limestone Group strata. That Lower Limestone Group strata originally covered a wide area here is shown by the occurrence of outliers of this age resting unconformably on Lower Old Red Sandstone rocks east of the Douglas Valley.[1] We have not yet sufficient evidence to decide the age of the unconformity but the rapid nature of the overlap suggests that it was due to uplift and erosion in early Millstone Grit times rather than to attenuation or non-deposition of the Carboniferous Limestone.

(2) Two sections in the neighbourhood of Ayr (Sheet 15) may also be referred to in this connection. Mr. V. A. Eyles has shown that a little to the east of Greenan Castle (on the coast south of Ayr) Millstone Grit lavas rest almost directly on the Cement-stone Group, while farther inland, near Loch Fergus in the Coylton district, volcanic rocks referred to the Millstone Grit rest upon Upper Calciferous Sandstone sediments.

### (2) Floral Subdivisions.

No further subdivision of the Carboniferous rocks is possible on the evidence of the fish fauna. While the forms characteristic of the Lower and Upper Carboniferous are specifically distinct, no ichthyological life-zones have been established within either of these major divisions. Fossil plants, however, have proved of great value in subdividing the Upper Carboniferous and the following classification by the late Dr. Kidston[2] is based on palaebotanical evidence:—

Radstockian Series (Upper Coal Measures): only the lower part of this series (Keele Group) is definitely represented in Scotland, i.e. upper part of Barren Red Measures of Canonbie (red shales of Jockie's Sike, near Riddings Junction)[3] and of Central Ayrshire.

[1] At Wedder Law and Limefield: *see* 'Summary of Progress for 1924,' *Mem. Geol. Surv.*, 1925, pp. 105-106.

[2] Footnote 1, p. 458.

[3] R. Kidston, 'The Fossil Plants of the Carboniferous Rocks of Canonbie, Dumfriesshire, and of parts of Cumberland and Northumberland,' *Trans. Roy. Soc.. Edinb.*, vol. xl, part iv, 1903, pp. 741-833.

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Staffordshire Series (Transition Series): includes the Newcastle-under-Lyme, Etruria Marl and Blackband groups of the English Midlands: not yet recognised in Scotland but possibly represented by part of the Barren Red Measures.[1]

Westphalian Series (Middle Coal Measures): represented in Scotland by the lower part of the Barren Red Measures and upper part of the Productive Coal Measures: Byre Burn Coal Group of Canonbie.

Lanarkian Series (Lower Coal Measures): represented in Scotland by the lower (and greater) part of the Productive Coal Measures, and by the upper part (approximately two-thirds) of the Millstone Grit: Rowanburn Coal Group of Canonbie.

No palaeobotanical subdivisions of the Lower Carboniferous have been established, but it should be noted that there is some evidence for a change of flora at the close of Calciferous Sandstone times, correlated with the widespread transgression of the Hurlet Limestone sea; certain forms such as *Telangium* (*Sphenopteris*) *affine* L. & H. and *Adiantites antiquus* (Ett.) are confined to the Calciferous Sandstone Series, while the Lower Carboniferous species of *Calamites* are, with a few rare exceptions, restricted to the Carboniferous Limestone Series.

It may be useful to present in tabular form at this point the basis of the palaeobotanical classification.[2]

[1] Plant remains, it should be remembered, are of comparatively rare occurrence in the Barren Red Measures.

[2] This table was prepared in 1927. My colleague Dr. R. Crookall has since then kindly verified the plant names, and I have gladly embodied the suggestions he makes.

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**UPPER CARBONIFEROUS.**

Part of Barren Red Measures (only in Liddesdale and Ayrshire)

**RADSTOCKIAN** (Only Keele Group represented in Scotland).
= UPPER COAL MEASURES. The Cyatheites-Pecopterids [e.g. *Asterotheca arborescens* (Schl.) and *Acitheca polymorpha* Brongt.] are distinctive. *Calamites* and *Lepidodendron* infrequent.

**STAFFORDIAN**
= TRANSITION SERIES. Flora transitional.

Upper part of Productive Coal Measures and lower part of Barren Red Measures

**WESTPHALIAN** — Middle Coal Measures

*Sigillaria* very abundant.
*Lepidodendron* abundant.
*Calamites* common.
Characterisitc species include *Asterotheca miltoni* (Artis), *Dactylotheca plumosa* (Artis); and examples of the genera *Odontopteris, Linopteris, Neuropteris, Lonchopteris, Alethopteris and Mariopteris.* Many typical *Sphenopterids.*
The dividing line is now drawn in the Central Coalfield at the Ell Coal (*see* p. 467).

Upper 2/3 of Millstone Grit and greater part of Productive Coal Measures

Many Westphalian species not found or very rare in Lanarkian →
← Some species restricted to Lanarkian →
← Many species common to both

**LANARKIAN** — Lower Coal Measures

*Sigillaria* not common.
Lepidodendron fairly common (especially *L. aculeatum* Sternb., and *L. obovatum* Sternb.) *Calamites suckowi* Brongt. and *C. undulatus* Sternb. common; most other species of *Calamites* rare.
Common forms are:—*Mariopteris nervosa* (Brongt.), *Neuropteris heterophylla* Brongt., *N. gigantea* Sternb., *Renaultia gracilis* (Brongt.) Rarer species occur, some of which are restricted to the Lanarkian.

→ *Calamites* with ribs on pith casts alternating at nodes

**PLANT BREAK:** With one or two exceptions the Floras above and below this line are specifically distinct.

*Calamites* ← with some ribs alternating at nodes, others passing the nodes without alternating as in *Asterocalamites*

**LOWER CARBONIFEROUS.**

Calciferous Sandstone and Carboniferous Limestone Series

*Pitys*
*Sigillaria* very rare.
*Lepidodendron* abundant, especially *L. veltheimianum* Sternb.
*Calamites* rare (six species in Britain).
*Asterocalamites scrobiculatus* (Schl.) occurs throughout.
Pteridosperms represented by many species, belonging especially to the *Sphenopterideae*

Carboniferous Limestone Series

*Calamites* generally restricted to upper part; *Calamites haueri* Stur, *C. ramifer* Stur, *C. taitiana* K & J. *Diplotmema adiantoides* (Schl.) (= *Sphenopteris elegans* Brongt.) common.

Calciferous Sandstone Series

*Telangium* (*Sphenopteris affine* (L. & H.) and *Adiantites antiquus* (Ett.) are both confined to this Series.
*Diplotmema adiantoides* (Schl.) (= Sphenopteris elegans Brongt.) rare.
*Rhacopteris* sp.
*Calamites* very rare.

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The Lanarkian, Westphalian and Staffordian of this table correspond with the Upper Westphalian of Western Europe as defined by de Lapparent[1] and other writers.[2] The Radstockian was regarded by Kidston as of Lower Stephanian[3] age, but other authorities prefer to include it in the Upper Westphalian. It was to avoid the use of the ambiguous term Westphalian that Prof. W. W. Watts[4] suggested the term Yorkian as a more suitable designation for Kidston's second series. The Lower Carboniferous of the table given would thus correspond to the Lower Westphalian and Dinantian of Western Europe. It should be noted that some continental authorities[5] use Westphalian and Namurian for the Upper and Lower Westphalian of de Lapparent. There is thus a great deal of confusion as regards the use of the term Westphalian. More recently Davies and Trueman[6] have utilised the non-marine lamellibranchs to subdivide the English Coal Measures and have shown that they fall into two major subdivisions—a higher one comprising the *Anthracomya tenuis* and *A. phillipsi* Zones, and a lower one comprising the *A. pulchra*, *Carbonicola similis*, *Anthracomya modiolaris* and *Carbonicola ovalis* Zones. For these two subdivisions Trueman[7] has suggested the terms Upper and Lower Westphalian. Trueman's Upper Westphalian corresponds fairly closely with Kidston's Radstockian and Staffordian, while Kidston's Westphalian would fall into the upper part of Trueman's Lower Westphalian. When the floral and faunal successions come to be more closely correlated it will clearly be necessary to discard much of the terminology now employed, and to make use of less ambiguous terms, for the various subdivisions.

In regard to the subdivisions of the Upper Carboniferous rocks it should be noted that they are mainly distinguished by floral *assemblages*, although certain species are confined to one particular

[1] *See* 'Geologie,' 5th ed., 1906, vol. II, p. 889.

[2] e.g. B. Kukuk, in *Congrès de Stratigraphie Carbonifère*: 1928, table opposite p. 448.

[3] From the Latin form for St. Etienne.

[4] 'Carboniferous Nomenclature,' *Geol. Mag.*, vol. lix, 1922, p. 238.

[5] e.g. W. J. Jongmans, in *Congrès de Stratigraphie Carbonifère*, Heerlen, 1928, table opposite p. 394.

[6] 'A Revision of the Non-Marine Lamellibranchs of the Coal-Measures,' *Quart. Journ. Geol. Soc.*, vol. lxxxiii, 1927, pp. 210-259.

[7] 'A Note on the Classification of the Coal-Measures,' *Geol. Mag.*, 1929, pp. 495-499.

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series. Plants common to both Lanarkian and Yorkian, for example, are, as a rule, much more abundant in the latter, while the assemblages characteristic of these two series are absent from the Radstockian. In the upper part of the Staffordian or Transition Series again Yorkian plants are rare, but they become increasingly more abundant in the middle portion, and in the lowest (or Blackband) group form the dominant part of the flora. In the case of the Upper Carboniferous of Scotland it must be clearly understood that the Lanarkian flora is by far the richest and most varied. The Yorkian and Staffordian floras on the other hand attain their greatest development in the English Midlands.

Practically all the valuable coals of the Scottish Coal Measures fall within the Lanarkian; in the Midlands, on the other hand, the principal seams are found in the Westphalian or Yorkian Series (Middle Coal Measures).

A few words may be added as to the approximate stratigraphical horizons at which the limits of these floras are drawn in Scotland. The dividing line between Lanarkian and Westphalian (or Yorkian) was taken by Kidston at the Ell Coal of Lanarkshire.[1] The seam is probably represented in the North Ayrshire sequence by the McNaught Coal which in turn is certainly the equivalent of the Ell of Central Ayrshire. This dividing line must, however, be regarded as approximate only; for example, the plants obtained from a horizon a few fathoms *below* the Ell in the Garrion Burn at Wishaw[2] indicate a Westphalian age. The upper limit of the Westphalian again may be tentatively drawn at, or a short distance above, Skipsey's Marine Band (the Mansfield Marine Band of the English Midlands: *see* p. 484). In the Ayrshire succession the highest Barren Red Measures are assigned to the Radstockian (Keele Group), the base of which may be drawn, again quite provisionally, at a horizon approximately 1500 ft. or so above Skipsey's Marine Band[3] (or its estimated position in the sequence). One point should be noted in this connection. Kidston drew the base of his Staffordian Series in North Staf-

[1] *See* ' Economic Geology of the Central Coalfield, Area V,' *Mem. Geol. Surv.*, 1916, p. 126; 2nd ed. 1926, p. 146.

[2] ' *Trans. Geol. Soc. Glasg.*, vol. xiv, part iii, 1911, p. 288.

[3] For the evidence for Radstockian plants *see* R. Kidston *in* ' Summary of Progress for 1907,' *Mem. Geol. Surv.*, 1908, p. 112 and R. Crookall *in* ' Geology of N. Ayrshire,' *Mem. Geol. Surv.*, 1929.

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fordshire at the base of the Upper Coal Measures (i.e. base of Blackband Group). Little, however, appears to be known of the flora of the strata between this datum-line and the Mansfield Marine Band in the upper part of the Middle Coal Measures, and further research may possibly show that the latter forms a more precise base for the Staffordian.[1] In that case Kidston's Staffordian will correspond very closely with Trueman's *Phillipsi* Zone.

### (3) Faunal Subdivisions.

A parallel statement of the subdivisions of the Scottish Carboniferous, based on the evidence of the faunas, is given in Figure 2. This figure shows the fossils that have proved of particular value for correlation purposes within Scotland and one or two that help to link the Scottish succession with that of England (*see* p. 473). It will be seen that the 'index' or 'key' fossils are few, although their number will certainly be added to as our knowledge advances:—

(a) *Productus giganteus* (Mart.), confined to the lowest limestones in the Lower Limestone Group (Hurlet, Main, Dockra, Hawthorn, etc.) and to the uppermost beds of the Calciferous Sandstone Series (Hollybush Limestone of Renfrewshire; Broadstone Limestone of Ayrshire; *P. giganteus* Limestone of Coalburn). The giganteid *Productus* found in the Upper Limestone Group is not a true *P. giganteus* but a much smaller, more globose, and more finely-striated form.

(b) *Sanguinolites abdenensis* Eth. is the characteristic member of the "Abden fauna"[2] found immediately below the Hurlet Limestone. It occurs, however, at lower levels.

(c) *Saccammina carteri* Brady characterises the limestones in the lower part of the Lower Limestone Group, above the Hurlet.[3]

(d) *Posidonomya corrugata* Eth., and *Ambocoelia urei* (Flem.). are characteristic of the upper part of the same group (Hosie Limestones), and the former is specially so of the shales associated with the Top Hosie.

(e) A somewhat spinose variety of *Productus latissimus* J. Sow

[1] *See* footnote (2), p. 482.

[2] *See* p. 518.

[3] e.g. Middle Skateraw of Dunbar; No. 2 Limestone Tyne Water (Midlothian); Craigenhill Limestone of Carluke; Limestone above Hawthorn of Coalburn.

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is confined to the lower part of the Upper Limestone Group and is a characteristic form of the Index Limestone.

(f) "*Edmondia*" *punctatella* (Jones) is restricted to the under side of the Calmy Limestone.

(g) *Nautilus* (*Discites*) *nodiferus* Armstrong, recently renamed *Tylonautilus nodiferus*,[1] is confined to the upper part of the Upper Limestone Group (Calmy and Castlecary Limestones, mainly the former).

(h) In the lower part of the Millstone Grit a fauna showing Upper Carboniferous affinities makes its appearance. This is the 'Nebraskan Fauna' of Wheelton Hind[2] and additional characteristic members are *Productus* cf. *cora* d'Orb., *P. carbonarius* de Kon., and the streptorhynchoid shell—*S. crenistria* var. *cylindrica* Dav.—now placed in the genus *Meekella*.

(i) The so-called 'mussels' of the Coal Measures belong to the genera *Carbonicola*, *Anthracomya* and *Naiadites*. Additional material and further research will be needed before comparison can be made with the zones established by Davies and Trueman for S. Wales. It is important to note, however, that *Anthracomya phillipsi* (Will) has recently been obtained in Central Ayrshire[3] along with *A. tenuis* Davies in beds lying 500 ft. or so above the base of the Barren Red Measures (*see* p. 482).

Rock groups again (e.g., the Lower and Upper Limestone groups) or even individual horizons (such as the 'Abden Bed' referred to above under (b) can be distinguished by means of their faunal *assemblages*. The fact that the Carboniferous Limestone Series of Scotland contains a middle group with a number of valuable coals renders any criteria for distinguishing the Upper Group from the Lower a matter of great practical importance. 'Index' fossils and faunal assemblages should be carefully looked for, but it may well happen in the case of a boring that the species obtained are neither sufficiently diagnostic nor sufficiently numerous to allow of a definite decision. The Carboniferous Limestone Series of Scotland belongs to the Upper Visean and would fall within subzones D2 and D3 of the *Dibun-*

[1] *See* p. 475.

[2] 'On the Lamellibranch and Gasteropod Fauna found in the Millstone Grit of Scotland,' *Trans. Roy. Soc. Edinb.*, 1908, vol. xlvi, p. 331. *See* above p. 459.

[3] J. Pringle and W. Manson, '*Anthracomya phillipsi* in the Barren Red Measures of Ayrshire,' Naturalist, 1928, p. 267.

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*ophyllum* Zone of Vaughan's Avonian classification.[1] The faunal distinctions between the Upper and Lower Limestone groups is largely a quantitative one, depending on the absence in the former of many forms found in the latter group.[2] The following points should be noted:—

(1) A number of species found in the Lower Limestones do not appear to occur in the Upper Limestones.

(2) Many forms are common to both groups but are much more abundant in the Lower.

(3) Others again are more common in the Upper Group.

(4) A few species are confined to the Upper Group.

The following are characteristic of the Lower Limestone Group:—

*Productus giganteus* (Mart); *Productus longispinus* J. Sow (coarse-ribbed form); *Pustula aculeata* (Mart); *P. defensa* Ivor Thomas; *P. pustulosa* (Phill); *P. spinulosa* (J. Sow); *Overtonia fimbriata* (J. de. C. Sow.); *Dielasma hastatum* (J. de C. Sow); *Ambocoelia urei* (Flem.); *Camarotoechia pleurodon* (Phill.); *Athyris planosulcata* Phill.; *Rhipidomella michelini* (L'Eveillé); *Schellwienella crenistria* (Phill.); *Naiadites crassa* (Flem.), *Posidonomya corrugata* Eth., and *Sanguinolites abdenensis* Eth. A few forms such as *Saccammina carteri* Brady,[3] and some of the corals (Fig. 2 and p. 474) have a narrow vertical range within the group.

The following are more characteristically Upper Limestone species:—*Productus latissimus* J. Sow; *P. costatus* J. de C. Sow. *P. longispinus* J. Sow (fine-ribbed form); *P. sinuatus* de Kon; *Buxtonia scabricula* (Mart.); *Rhynchopora youngi* Dav.; while confined to narrow portions of this group are "*Edmondia*" *punctatella* (Jones), *Tylonautilus nodiferus* (Armstrong); *Derbyia* and *Meekella* species, and a dwarfed rather globose giganteid *Productus*.

In the above lists only a few animal groups have been drawn upon for examples. As regards the corals, bryozoa, echinodermata and sponges the Lower Limestone fauna is much richer and more varied than that of the Upper Limestones. In certain areas corals, for example, are not known from the latter group and

[1] A. Vaughan, 'The Palaeontological Sequence in the Carboniferous Limestone of the Bristol Area,' *Quart. Journ. Geol. Soc.*, 1905, vol. lxi, pp. 181-305

[2] Compare the difference between Lanarkian and Yorkian as regards floras.

[3] This form is recorded by H. B. Brady (*Pal. Soc.*, 1876), from the Castlecary Limestone; the record however is doubtful.

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in other areas where they are found the occurrences are as a rule isolated and few. Of the small gasteropod shells belonging to *Aclisina*, *Murchisonia* and *Hypergonia* a number of species are common to both groups, but some are recorded only from Lower Limestone, some only from Upper Limestone, strata.[1] The variation in faunal assemblages seems to be due to geographical change and to migration rather than to any clearly expressed evolutionary process. Certain species flourished for a time and disappeared from the area, but returned as soon as suitable conditions recurred.

(4) COMPARISONS WITH THE NORTH OF ENGLAND.

(a) *Lower Carboniferous Rocks.* It seems desirable at this stage to try and link up the Scottish Lower Carboniferous succession with that of the north-east and north-west of England (Northumberland and Cumberland). A number of important points of comparison have been established as will be seen from the list given below, but much work remains to be done on both the morphology and distribution of the fossils before satisfactory detailed correlations can be made. More particularly is there a need for critical examination and comparison of the species listed from different localities, for more exact standards of definition, and for a comprehensive study of the relations between distribution and conditions of deposit. The correlations put forward below (Plate IV) must therefore be regarded meanwhile as in a large measure tentative, but they will serve at least as a basis for further research.

The sections given on Plate IV show the general succession in the Lower Carboniferous rocks of (1) West of Scotland, (2) East of Scotland, (3) North Northumberland, and (4) Cumberland (Brampton district). Correlations are also made with the Whitehaven district (5) and with the Westmoreland Pennine area (6). In regard to these sections the following points should be noted:—

(a) In Section (1) the Calciferous Sandstone (Clyde Plateau) Lavas, perhaps 2000 to 3000 feet thick, are underlain by a variable thickness of almost unfossiliferous lagoonal deposits consisting of alternating shales and thin cementstone bands, with subordinate

[1] *See* Mrs. J. Longstaff, 'Supplementary Notes on *Aclisina* de Koninck and *Aclisoides* Donald,' *Quart. Journ. Geol. Soc.*, vol. lxxiii, 1917, pp. 59-83; 'A Revision of the British Carboniferous Murchisonidae,' *ibid.*, vol. lxxxii, 1926, pp. 526-555.

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sandstones. These beds, which in the type locality at Ballagan[1] in Strathblane reach a thickness of about 600 feet,[2] pass conformably downwards into the Upper Old Red Sandstone. Sometimes, however, the lavas rest directly or almost directly on strata referred to the Upper Old Red, as in the Garrel Burn on the south slopes of the Campsie Fells near Kilsyth, or in the country north of Ardrossan (Beith Hills).

(b) The sequence shown in Section (2) from the Gilmerton Limestone upwards is that found in the Midlothian Basin; the lower part represents the magnificent section of Calciferous Sandstone rocks exposed on the coast of East Fife to the west of Anstruther, the details of which were worked out in so masterly a fashion by Kirkby.[3] Below these Anstruther beds I would place most of the strata exposed near Randerstone between Randerstone Castle and Cambo Ness.[4] The Randerstone beds in turn overlie a thin group of strata with a Cementstone facies which include at their base a band of cherty cornstone such as characterises the transition beds between the Upper Old Red and the Carboniferous. The Randerstone limestones I correlate tentatively with the upper part of the Liddisdale Cementstone Series (see below).

(c) The Brampton sequence is described in the 'Summary of Progress for 1925' (*Mem. Geol. Surv.*, 1926, pp. 78-82) and Section (4) is based on the details given there (p. 81).[5]

(d) The sequence of limestones in the Whitehaven district[6] of West Cumberland is shown in Section (5). In this district the Snebro Gill Beds above the First Limestone have yielded *Tylonautilus nodiferus* and must be referred to a horizon high up in the Upper Limestone Group. The evidence suggests that an

[1] Hence the name Ballagan Group, often used as a synonym for Cementstone Group.

[2] Above them is the Spout of Ballagan Sandstone, a hard white siliceous rock, 100 feet thick.

[3] *See* 'Geology of East Fife,' *Mem. Geol. Surv.*, 1902, pp. 77-97.

[4] Kirkby's "Randerstone Beds"; *Loc. cit.*, pp. 123-126; or *Trans. Edinb. Geol. Soc.*, vol. viii, part i, 1901, p. 61.

[5] *See also* F. M. Trotter and S. E. Hollingworth, 'The Upper Limestone Group and Millstone Grit of N.E. Cumberland'; in 'Summ. of Progress for 1926,' *Mem. Geol. Surv.*, 1927, pp. 98-107; F. M. Trotter, 'Lower Part of the Carboniferous Limestone Series in the Brampton and Gilsland Districts,' 'S. of P. for 1925,' 1926, pp. 157-161.

[6] C. Edmonds, 'The Carboniferous Limestone Series of West Cumberland,' *Geol. Mag.*, vol. lix, 1922, pp. 74-83 *and* 117-131.

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unconformity may be present above the First Limestone at the base of the overlying Hensingham Grit.

The evidence for the comparisons of the Scottish and English sequences that are shown on Plate IV may now be briefly outlined. Reference should be made here, however, to the important contribution to this subject made by Gunn[1] in 1898. Gunn recognised that "the Edge Coal Group of Midlothian is but an extraordinary development of the Lickar Coals," showed that the Lower Limestone group was represented in the North of England by part of the Yoredale Series, and made a number of valuable correlations of the Northumberland sequence with that found on the coast at Cockburnspath and Dunbar. With the fuller information now at our disposal it is possible to provide a more detailed and more exact comparison.

(1) An important index horizon in the succession found in North-West England is the *Girvanella* Nodular Bed, thus described by Garwood[2]: "this is one of the most constant horizons in the North of England, and occurs at intervals, from the extreme north of Northumberland to Penyghent. It invariably forms the base of the Upper Dibunophyllum Sub-Zone." The *Girvanella* Band has been recognised in West Cumberland (Rough Beds)[3] and in the same county is correlated with the Bankhouses Limestone of the Brampton district.[4] It is represented in the Northumberland sequence by the Oxford Limestone with its abundant *Girvanella* nodules.[5] General stratigraphical considerations again suggest that its equivalent in the Scottish succession is to be found in one of the limestones at or near the base of the Scottish Lower Limestone Group—possibly the Hurlet or Main Limestone.

(2) The *Girvanella* horizon is succeeded by a group of beds characterised by *Saccammina carteri*. This fossil is abundant in

[1] W. Gunn, 'Correlation of the Lower Carboniferous Rocks of England and Scotland,' *Geol. Mag.*, 1898, pp. 342-349; or *Trans., Edinb. Geol. Soc.*, vol. vii, part iv, 1899, pp. 361-367.

[2] E. J. Garwood, 'The Lower Carboniferous Succession in the North-West of England,' *Quart. Journ. Geol. Soc.*, vol. lxviii, 1912, p. 482.

[3] C. Edmonds, 'The Carboniferous Limestone Series of West Cumberland,' *Geol. Mag.*, 1922, p. 126.

[4] *See* F. M. Trotter in 'Summary of Progress for 1925,' *Mem. Geol. Surv.*, 1926, p. 160.

[5] Also found, though less abundantly, in the Dun Limestone.



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the Little Strickland Limestone of the Shap country, in the Tyne Bottom Limestone of Cumberland (where its range includes the Scar, the Four Fathom, and even the Great Limestone), in the Eelwell-Acre group of North Northumberland, and in the limestone or limestones that succeed the Main in the Lower Limestone sequence of Scotland.[1]

(3) The Acre Limestone of Northumberland is, on faunal and lithological grounds, identified with the Middle Skateraw, one of the lower limestones in the Lower Limestone Group of the Dunbar coast.[2] The Acre Limestone is characterised by the abundance of *Sacammina carteri*[3] and the same fossil forms a band near the top of the Middle Skateraw on the coast south-east of Dunbar,[4] and in the No. 2 limestone of the Tyne Water section on the south-east side of the Midlothian Basin (Upper Limestone of Middleton quarries).[5] Further, my colleague Mr. R. G. Carruthers informs me that the following corals are, so far as he knows, confined to the Acre Limestone in N. Northumberland and to the Middle Skateraw in the East of Scotland: *Cyathaxonia cornu*, *Zaphrentis eruca*, and a new species of *Caninia*.

(4) The Hosie Limestones of the Scottish succession would thus appear to be represented in Northumberland by the Sandbanks (or Eight Yard) and Dryburn Limestones and in Cumberland by the Four Fathom and Great. This correlation is strengthened by the occurrence of *Posidonomya corrugata* Eth., the index fossil of the Hosie group, in beds underlying the Great Limestone, in the cores of a boring put down near Crook in the county of Durham.[6]

(5) Corresponding to the Limestone Coal Group in Scotland (Edge Coals of Midlothian, Kilnholm Coals of Liddisdale) is the

[1] *See* footnote 3, p. 468.

[2] *Cf.* W. Gunn, 'Correlation of the Lower Carboniferous Rocks of England and Scotland,' *Geol. Mag.*, 1898, p. 347 and *Trans., Edinb. Geol. Soc.*, vol. vii, part iv, 1899, p. 366. Mr. J. Bennie, it should be noted, came independently to the same conclusion (*loc. cit.*).

[3] 'Geology of Berwick-on-Tweed, Norham and Scremerston,' *Mem. Geol. Surv.*, 1926, p. 25.

[4] 'Geology of East Lothian,' *Mem. Geol. Surv.*, 1910, p. 137, *See also* R. Etheridge, 'The Occurrence of Foraminifera (*Saccammina Carteri*, Brady) in the Carboniferous Limestone Series of the East of Scotland,' *Trans., Edinb. Geol. Soc.*, vol. ii, part ii, 1873, p. 225.

[5] 'Geology of the Neighbourhood of Edinburgh,' *Mem. Geol. Surv.*, 1910, pp. 190-1.

[6] G. W. Lee *in* 'Summary of Progress for 1923,' *Mem. Geol. Surv.*, 1924, p. 148.

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very much thinner group containing in Northumberland the Lickar or Lowick seams and in Cumberland the Oakwood Coal.

(6) The Index Limestone is thus on approximately the same horizon as the Lickar Limestone and is represented in Cumberland by one of the Oakwood limestones—probably the Middle Oakwood.

(7) The Calmy (or Arden) Limestone may in turn be identified with the Thornboro' of Cumberland. Pringle and Jackson[1] have recently shown that *Tylonautilus nodiferus* is an index fossil that can be used as a guide in identifying these horizons. Armstrong, who originally described this shell under the name *Nautilus* (*Discites*) *nodiferus*,[2] commented on its narrow vertical range; in Scotland it is specially characteristic of the Calmy Limestone although its range includes the Castlecary. In the North of England it appears to be confined to the Thornboro' Limestone or to beds which are referable to the upper part of the Lower Carboniferous and are therefore at or near the position of the Thornboro'. It occurs, for example, in the Thornboro' Limestone at Styford and in the Harlow Hill Limestone of Cross Eye quarries (West Northumberland).

(8) The Fell Top Limestones may be tentatively correlated with the Castlecary or Levenseat Limestone of the Scottish area. Their lamellibranch and brachiopod fauna (including *Productus* cf. *cora* d'Orb) suggested to Pringle and Jackson[3] a comparison with the Garngad Road shales of the Glasgow district[4] which have been referred to a low horizon of the Scottish Millstone Grit. The Garngad Road fossils, however, are not sufficiently diagnostic and do not preclude the possibility of a somewhat earlier age.

When we pass to the strata below the Hurlet and Oxford horizons we are on much less firm ground. Throughout by far the greater part of the sequence we have to rely for purposes of comparison on broad lithological criteria. The life-zones established in the English North-West province[5] have not been recognised in the more varied deposits found in Scotland, although

[1] 'Tylonautilus nodiferus: A Carboniferous Guide Fossil,' *Naturalist*, 1928 pp. 373-378.

[2] *Trans. Geol. Soc. Glasgow*, vol. ii, part 1, 1865, pp. 74-75.

[3] *Loc. cit.*, p. 376.

[4] *See* 'Geology of the Glasgow District,' *Mem. Geol. Surv.*, 1925, p. 84.

[5] *See* E. J. Garwood, 'The Lower Carboniferous Succession in the North-West of England,' Quart. Journ., *Geol. Soc.*, vol. lxviii, 1912, Fig. 2, p. 452.

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further research and a more critical examination of the material may well yield valuable results. To this generalisation one important exception at least must be noted. Where the sequence in the English North-West province is most fully developed, the base of the C1 zone is defined by a well-marked band containing *Camarotoechia proava*, while a little higher in the sequence occurs a characteristic bed of dark-coloured impure dolomitic limestone carrying nodules or layers composed of algae:[1] this band forms the base of Garwood's *Seminula gregaria* sub-zone. Both the Algal Limestone and the *Camarotoechia proava* Band have proved of great value in establishing correlations in North-West England. The shell recorded from the limestones in the upper part of the Liddisdale Cementstone Series (Thorlieshope and Larriston Burn Limestones) as *Camarotoechia crumena*[2] is identical with *C. proava*, while the fossil listed by Kirkby[3] under the name '*Rhynchonella pleurodon*' as characteristic of the seventh limestone of his Randerstone section is probably referable to the same species; it is associated there with a nodular algal limestone.[4] On this evidence I have tentatively assigned a C1 age to the Randerstone Beds and to their probable equivalents in the Liddisdale succession.

Of the general equivalence of the various subdivisions shown in Plate IV below the Hurlet and Oxford horizons there can be little doubt. Thus the Scremerston Coal Group of Northumberland corresponds to part of the Scottish Oil-Shale Group, the Fell Sandstone to the strata which include in the Lothians the Granton Sandstone and in Fifeshire the Billowness Sandstone. Comparison with the Cumberland sequence again shows that the Scremerston Series of fresh-water or estuarine deposits is repreented there by marine beds (still containing coals locally however), and is probably equivalent to the greater part, if not all, of the *Seminula* Zone (S) and the lower portion of the Lower *Dibunophyllum* Zone (D1);[5] the Fell Sandstone in Cumberland

[1] E. J. Garwood, *loc. cit.*

[2] *See* B. N. Peach and J. Horne, 'The Canonbie Coalfield,' *Trans. Roy. Soc. Edinb.*, 1903, vol. xl, p. 842.

[3] *See* 'Geology of East Fife,' *Mem. Geol. Surv.*, 1902, p. 124.

[4] It was my colleague, Mr. John Pringle, who first suggested (a year or so ago) that algal beds might be present in this section in association with the '*Rhynchonella pleurodon*' band. Recent examination has shown this to be the case.

[5] *See* F. M. Trotter, 'Lower Part of the Carboniferous Limestone Series in the Brampton and Gilsland Districts,' in 'Summary of Progress for 1925,' *Mem. Geol. Surv.*, 1926, p. 160.

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contains thin fossiliferous limestones yielding a C2 fauna and it is possible that some at least of the limestones present near the base of the Anstruther coast section of E. Fife may prove to be the equivalents of these. The relation of the Randerstone Beds to the Anstruther limestones is by no means clear, but I have tentatively assigned the former to a still lower stratigraphical level.

The difficulty of establishing more definite correlations must be set down to the varying character of the sediments and to the conditions under which they were accumulated. The beds below the Hurlet or Main Limestone in Scotland were laid down in lagoons (Cementstone facies) or in more or less land-locked estuaries or gulfs to which the sea, however, had at times access. The Upper Calciferous Sandstone Series of the Lothians, with its characteristic marls and oil-shales, appears to have been accumulated in an estuary surrounded to north, west and south by land areas composed largely of volcanic rocks; to the east and north-east it was separated from the East Fife area by sand-bars, but during periods of depression these were broken down and marine conditions prevailed for a time.[1] Towards the close of Calciferous Sandstone times differential crustal movements supervened, submerging most of the old land areas and leading to the great transgression of the Hurlet Limestone sea. In the North-East Cumberland area, on the other hand, the period of maximum submergence occurred at an earlier date, during the deposition of the lowest beds of the D1 sub-zone. Below this horizon the strata are of a shallow-water facies, such as might be laid down in land-locked gulfs under conditions that allowed ready access to the sea; they are more marine in character than their equivalents in Northumberland, while the Liddisdale succession appears to indicate an intermediate stage. The open sea lay to the south-west and west and deposition took place in an estuary or trough extending across North-East Cumberland and Northumberland. The northern margin of this trough was formed by a ridge of older rocks stretching across what is now the Southern Uplands of Scotland and separating it from the estuary in which the Calciferous Sandstone Series of the Lothians and Fife was accumulated. The basement beds of the Whitehaven and Westmorland Pennine

[1] For the evidence for marine horizons *see* p. 515.

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areas (Plate IV, Sections 5 and 6) represent the deposits laid down close to the southern margin of the trough. Messrs. Trotter and Hollingworth in a recent paper[1] summarise their conclusions as regards the southward extension of the area of deposition: "The southern limits of the trough approximately coincide with the northern limits of a ridge which according to Goodchild[2] extended from the Isle of Man to the Durham coast. Woolacott[3] doubted its existence in Durham, but work in North-East Cumberland, and the evidence of the Isle of Man bores favour Goodchild's view in confirming the northern boundary of the ridge." We must regard the Scottish and North of England areas as portions of a kind of archipelago on the fringes of the Carboniferous sea; the lower zones of the Bristol district are entirely absent[4] and the Carboniferous sea had thus invaded the latter area some time before submergence of the North-West province began.

The fossil zones established for the Cumberland succession are indicated in Plate IV. The Randerstone beds in Scotland have, as already stated, been tentatively assigned a C1 age; the higher part of the Scottish succession, from the Hollybush Limestone upwards to the Castlecary, is referable to the D2 and D3 sub-zones. The zonal equivalents given for the intermediate beds, however, (i.e. greater part of the Calciferous Sandstone Series) are only suggestions.

It should be carefully noted that the Lower Limestone Group of Scotland is roughly the equivalent of the Middle Limestone Group of Northumberland and Cumberland, while the Limestone Coal and Upper Limestone groups together correspond to the Upper Limestones of the latter areas. The Lower Limestone Group of Cumberland again has a greater stratigraphical range than the Lower Limestones of Northumberland (the base of which is taken at the Dun Limestone) and corresponds to the Upper part of the Scottish Calciferous Sandstone.

[1] "On the Upper Limestone Group and 'Millstone Grit' of North-East Cumberland," in 'Summary of Progress for 1926,' *Mem. Geol. Surv.*, 1927, p. 105.

[2] 'An Outline of the Geological History of the Eden Valley or Edenside,' *Proc. Geol. Assoc.*, vol. xi, 1889, p. 269.

[3] 'On a Boring at Roddymoor Colliery, near Crook, Co. Durham,' *Geol. Mag.*, 1923, p. 53.

[4] There is a possible exception to this in the Pinskey Gill beds of Ravenstonedale, which, according to Garwood (*loc. cit.* p. 546) "probably represent some portion of the *Zaphrentis* Zone (Z) of the Bristol sequence."

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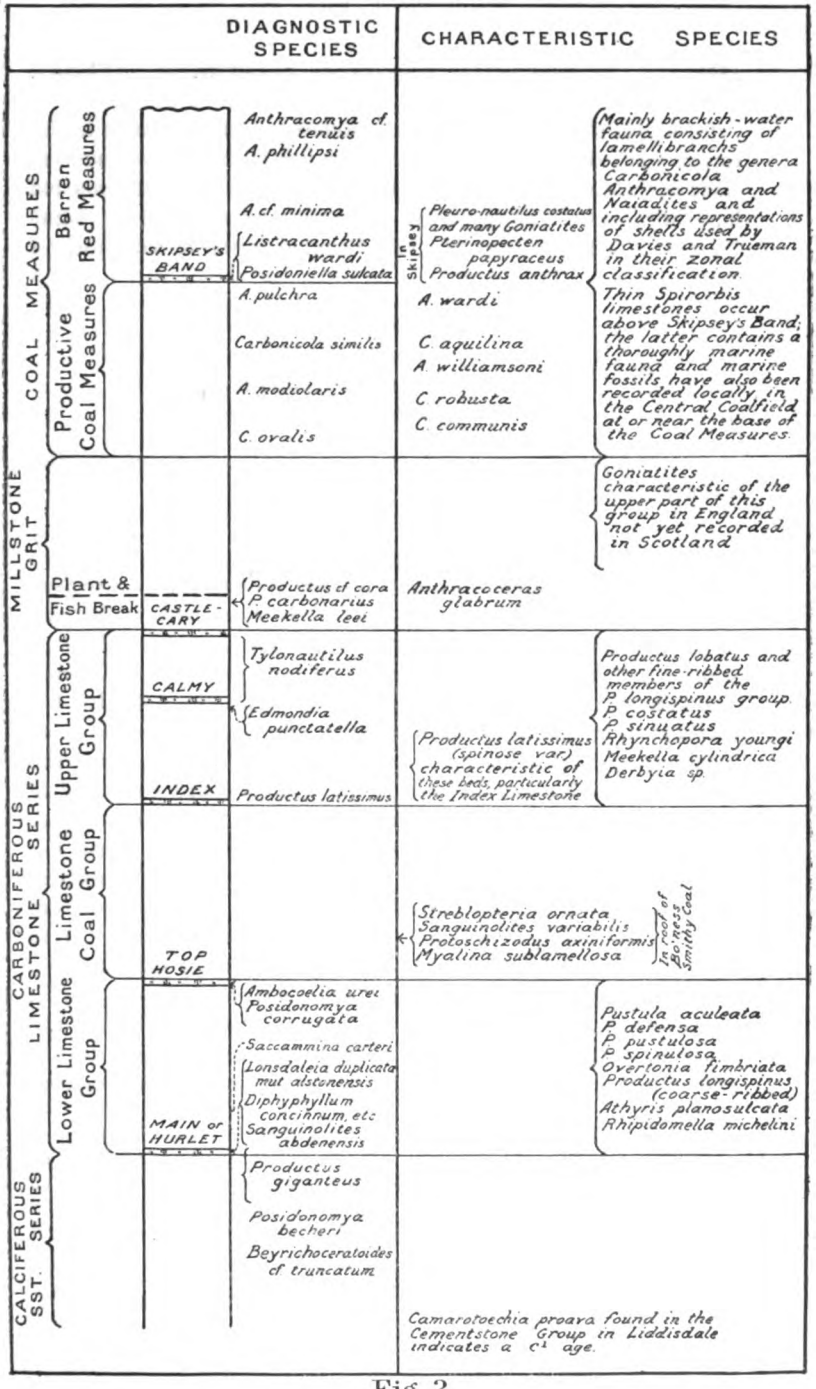


Fig. 2

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(b) *Upper Carboniferous Rocks.*—Reference may be made to the recent work done in England towards establishing zonal successions in these rocks by means of the goniatites and the non-marine lamellibranchs. The goniatite succession recognised by Bisat for the North of England (Mid-Pennine area) is summarised below:—[1]

Lancastrian
- *Gastrioceras* beds—G.
- *Reticuloceras* beds—R.
- *Homoceras* beds—H.
- *Eumorphoceras* beds—E.

Dividing line between Upper and Lower Carboniferous Goniatite Faunas.

*Goniatites* s. str. beds—P.

Each of these genus zones is subdivided further into species zones; thus E is subdivided into a lower zone (E1) characterised by *E. pseudobilingue* and an upper zone (E2) characterised by *E. bisulcatum.* The beds characterised successively by *Eumorphoceras, Homoceras, Reticuloceras,* and *Gastrioceras* form Bisat's Lancastrian Series, which corresponds approximately in the lithological terminology with the Millstone Grit and Lower Coal Measures of Yorkshire and Lancashire. Bisat in 1924 drew the upper limit of his Lancastrian at the Halifax Hard Bed Coal of Yorkshire (Bullion Mine of Lancashire) which lies near the base of the Lower Coal Measures, but has recently (1928, 1929) extended it to the top of the latter. None of the goniatites characteristic of Bisat's higher zones has yet been recorded from the Scottish Millstone Grit, but goniatite fragments obtained from near the base of this Series have been provisionally identified by him[2] as *Anthracoceras glabrum* and indicate a position in Upper E. or Lower H. In a section near Garngad Road Station in the Glasgow district and in shales referred to a low position in the Millstone Grit[3] a suite of lamellibranchs and gasteropods has been

[1] *See* W. S. Bisat, 'Carboniferous Goniatites of the North of England and their Zones,' *Proc. Yorks. Geol. Soc.*, vol. xx, part 1, 1924; 'Carboniferous Goniatite Zones of England and their Continental Equivalents,' *Congrès de Stratigraphie Carbonifère*, Heerlen, 1928, pp. 117-130 and plate VI; *also* Table of Carboniferous Goniatite Zones (Western Europe) *in* 'Handbook of the Geology of Great Britain,' 1929, facing p. 251.

[2] *Proc. Yorks. Geol. Soc.*, vol. xx, part i, p. 55.

[3] 'Geology of the Glasgow District,' *Mem. Geol. Surv.*, 1925, p. 84.

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obtained which closely resembles the fauna of the beds that in Cumberland succeed the Thornboro' Limestone.[1] This limestone, which may be correlated with the Calmy Limestone of Scotland (p. 475) has yielded in West Northumberland a poorly-preserved specimen of *Eumorphoceras*. The floral evidence again places the dividing line between Upper and Lower Carboniferous near the top of the lower third of the Millstone Grit in Scotland and at or near the junction of E and H in Bisat's Lancastrian.[2] If the base of the Lancastrian were taken at this higher horizon, as later work seems to indicate it should be, it would coincide with the base of Kidston's Lanarkian. Bisat's Lancastrian would thus correspond approximately with the Lanarkian of the floral classification.

Davies and Trueman,[3] following up the pioneer work of Wheelton Hind, have recently utilised the non-marine lamellibranchs to establish a zonal succession within the Coal Measures. The zones recognised by these authors in South Wales, are:—

(6) Zone of *Anthracomya tenuis*.
(5) Zone of *Anthracomya phillipsi*.
(4) Zone of *Anthracomya pulchra*.
(3) Zone of *Carbonicola similis*.
(2) Zone of *Anthracomya modiolaris*.
(1) Zone of *Carbonicola ovalis*.

A similar succession has been made out in North Staffordshire where, however, "no trace of shells resembling *Anthracomya tenuis* is known."[4] Trueman[5] refers to the base of Zone (5) as "the most important palaeontological break which has so far been detected in the Coal Measures," and suggests a division of the Upper Carboniferous into two major groups, the Upper Westphalian comprising Zones (5) and (6), and the Lower Westphalian including Zones (1) to (4). Little work has been done as yet as regards the distribution of the non-marine lamellibranchs in the

[1] J. Pringle and J. W. Jackson, 'Tylonautilus nodiferus: A Carboniferous Guide Fossil,' *Naturalist*, 1928, p. 377.

[2] Bisat, *loc. cit.*, p. 46; and J. W. Jackson, in *Journ. Manchester Geol. Assoc.*, vol. i, part 1, pp. 27-28.

[3] 'A Revision of the Non-Marine Lamellibranchs of the Coal Measures and a Discussion of their Zonal Sequence,' *Quart. Journ. Geol. Soc.*, vol. lxxxiii, 1927, pp. 210-257.

[4] *Ibid.*, p. 247 and Fig. 9.

[5] 'A Note on the Classification of the Coal Measures,' *Geol. Mag.*, 1929, pp. 496-7.

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Coal Measures of Scotland and there is undoubtedly a most important field for future research in this connection. It may be noted, however, that the following zonal forms have been obtained in Scotland (*see* Fig. 2).

(1) *A. tenuis* and *phillipsi* in the Barren Red Measures of Ayrshire at a horizon well above Skipsey's Marine Band.[1]

(2) *A. pulchra* in the Productive Coal Measures of Fife.

(3) *C. similis* in the Productive Coal Measures of Fife and Ayrshire.

(4) *A. modiolaris* in the Productive Coal Measures of Lanarkshire, Fifeshire and Ayrshire.

(5) *C. ovalis* in the Productive Coal Measures of Ayrshire and Midlothian.

It may be of some interest to present in tabular form the various classifications given for the Upper Carboniferous (Fig. 3). Little is known of the flora of the upper part of the Middle Coal Measures of the Midlands,[2] and the base of Kidston's Staffordian may yet be shown to agree closely with the base of Trueman's Upper Westphalian. The boundary between Kidston's Westphalian and Lanarkian appears to be very indefinite nor indeed does there seem to be much evidence to justify the continued use of the term Lanarkian. Bisat again has drawn the lower limit of the Lancastrian at the base of E, but it might well be taken at the base of H and would thus coincide more or less closely with the plant break of Kidston.

The question of the classification of the Upper Carboniferous is, however, far from being settled, and it may be necessary to take into consideration not only the flora but also the estuarine and marine faunas. In the last column of Fig. 3 I have suggested continuing the use of the Staffordian of Kidston for the higher beds, extending its range down to the base of Davies and Trueman's *Phillipsi* Zone. The Westphalian of Kidston might be replaced by the less ambiguous Yorkian of Watts and its base drawn at the horizon of the marine band overlying the Ganister or Halifax Hard Bed Coal of Yorkshire (Alton of Derbyshire,

[1] *See* J. Pringle and W. Manson, *Naturalist*, 1929, pp. 267-8.

[2] Quite recently Miss E. Dix ('On the Flora of the Upper Portion of the Coal Measure of North Staffordshire,' *Abstract of Proceedings Quart. Journ. Geol. Soc.*, May 8th, 1930) has shown that the base of the Staffordian must be drawn 400 ft. or so below the base of the Upper Coal Measures, i.e. that the Staffordian must be extended to include the upper part of the Middle Coal Measure. *See also* Dix, Pringle and Trueman on significance of term 'Lanarkian' in *Naturalist*, Sept., 1930.

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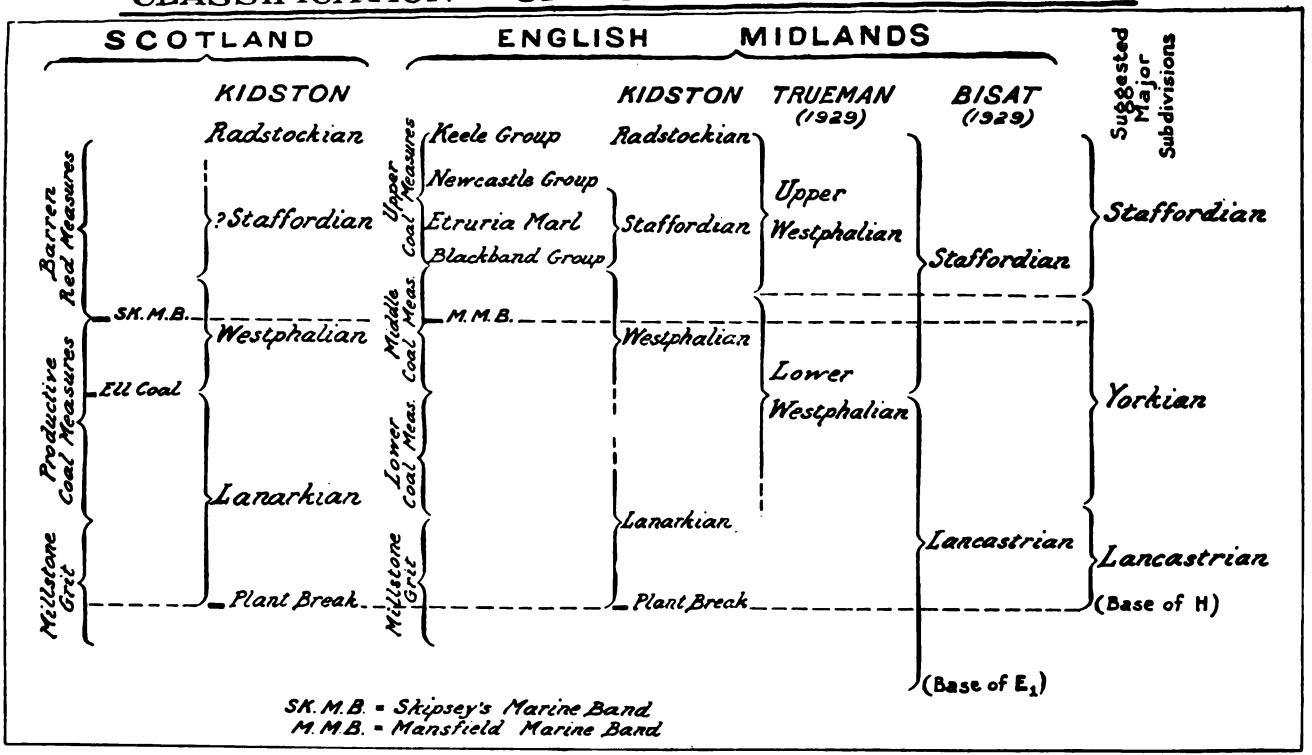


Fig. 3

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Bullion Mine of Lancashire). For the strata between this horizon and the base of H (Kidston's plant break) Bisat's term Lancastrian might be adopted.

It will be seen that in Fig 3 Skipsey's Marine Band is correlated with the Mansfield Marine Bed of the English Midlands. In the following note Mr. J. Pringle has kindly summarised the palaeontological evidence bearing on this important question.

" The possibility that Skipsey's Marine Band occupies the same stratigraphical position as that of the Mansfield Marine Band and its equivalents in England and Wales has been commented upon by numerous observers.[1] It is only within recent years, however, that palaeontological evidence has been forthcoming to enable a definite correlation to be made between these horizons. Fossils now known to be common to Skipsey's and the Mansfield Bed and its equivalents are as follows:—Crinoidal ossicles, *Chonetes laguessiana, Lingula mytiloides, Orbiculoidea nitida, Buxtonia scabricula, Productus anthrax, Spirifer sp. Posidoniella sulcata, Pterinopecten papyraceus, Protoschizodus axiniformis, Conularia quadrisulcata, Orthoceras attenuatum* and several species of Goniatites and Nautiloids. Conspicuous amongst the fishes are *Diplodus gibbosus* and *Listracanthus wardi*,[2] the latter species being practically confined to the Mansfield Bed.

Respecting the stratigraphical horizon of the Mansfield Marine Band in England and Wales, it has been shown that the bed falls within the zone of *Anthracomya pulchra* of Davies and Trueman's classification which is based on the non-marine lamellibranchs. In Scotland evidence that Skipsey's Band occurs in the same zone is gradually accumulating. In Fifeshire, Mr. W. Manson has obtained specimens of *Anthracomya pulchra* and *A. pumila* in shales not far below the marine bed, while in Ayrshire the occurrence of *Anthracomya phillipsi* in the Barren Red Measures

[1] *See*, J Smith and C. T. Clough, 'The Marine Beds near the Base of the Upper Carboniferous Red Barren Measures of Scotland,' *Sum. Prog. Geol. Survey for* 1907, pp. 127-136. W. Gibson, 'Coal in Great Britain,' 2nd edition, 1927, p. 285. J. Pringle, 'Fossils and Stratigraphy,' *Nature*, vol. cxxii, 1928, p. 835. D. A. Allan, 'The Stratigraphy of the British Carboniferous.' *Congrès de Stratigraphie Carbonifère*, Heerlen, 1927, 1928. J. Pringle and W. Manson, '*Anthracomya phillipsi* in the Barren Red Measures of Ayrshire,' *Naturalist*, 1929, p. 267.

[2] Collected by Mr. W. Manson, *See* 'Summary of Progress for 1929, Part i, *Mem. Geol. Surv.*, 1930, 35[1].

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at a level some distance above the marine bed suggests that Skipsey's Band in that county also lies within the *Pulchra* Zone."

## IV. LITHOLOGICAL SUBDIVISIONS.

The subdivisions of the Scottish Carboniferous outlined in Fig. 1, p. 454 (Calciferous Sandstone Series, Lower Limestone Group, Limestone Coal Group, Upper Limestone Group, Millstone Grit, Productive Coal Measures, Barren Red Measures) represent an essentially lithological classification. It will be noted that the palaeontological 'break' referred to in an earlier section occurs within the sandstones of the Millstone Grit Series. The boundary line between Lanarkian and Yorkian in the palaeobotanical classification is drawn at the horizon of the Ell Coal, high up in the Productive Coal Measures, while the representatives of the higher Staffordian and Radstockian series must be looked for within the Barren Red Measures (*see* p. 467). A short summary of the main characteristics of the lithological subdivisions in use is accordingly necessary at this point.

### (1) Barren Red Coal Measures.

This group (sometimes called Upper Barren Red Measures or Barren Red Sandstone Group), consists essentially of massive, usually soft and reddish sandstones, with variegated marly fireclays, purplish shales, occasional thin coals, and a few bands of impure limestone. The base of the group is drawn immediately above the shelly horizon known as Skipsey's Marine Band (p. 456); except in this band fossils are few. In addition to plant and fish remains there have been obtained locally estuarine mussels (*Anthracomya* sp.), freshwater entomostraca belonging to the genus *Carbonia*, and the annelid *Spirorbis*. The thin limestones recorded within the group at various localities do not have the persistent character of the true marine limestones and accordingly are of little use as index-horizons. The variable colouration of the group is a characteristic feature and the red staining of the sandstones would seem to be, largely at least, a secondary phenomenon. In the Central Coalfield reddening of the strata is seldom present below Skipsey's Band and the typical colouration may not begin until some distance above it; grey or white sandstones, again, may alternate with red sandstones and mottled clays. Professor E. B. Bailey has pointed out that the colour distribution is such as would be expected from oxidation in New Red Sandstone times of the iron carbonates and sulphides in the

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Carboniferous rocks. The Arran Carboniferous rocks, for example, are much thinner than their equivalents in Ayrshire and the red coloration in the former reaches a considerably lower stratigraphical level than in the latter; "it certainly continues well below the base of the Carboniferous limestone."[1] The sequence in the Barren Red Measures of the Hamilton area (one-inch Sheet 23) may be quoted by way of illustration:—

| | Ft. | in. |
|---|---|---|
| Red sandstones, with some fireclays .. .. .. | 144 | 0 |
| Purple fireclays and shales, with red marly sandstones | 72 | 0 |
| Red massive sandstones .. .. .. .. | 84 | 0 |
| Purplish fireclays and shales, with some thin coals (up to 12 in.) .. .. .. .. .. .. | 90 | 0 |
| Grey sandstones, with reddish bands .. .. .. | 78 | 0 |
| Lilac-coloured shales .. .. .. .. .. | 14 | 0 |
| Skipsey's Marine Band .. .. .. .. .. | 0 | 8 |

Barren Red Measures are present in Fife (Wemyss to Leven), Midlothian (Dalkeith), in the Central Coalfield (Hamilton, Uddingston, etc.), in the Douglas Valley, in Central and South Ayrshire, and at Sanquhar and Canonbie. The red sandstones (Devon Red Sandstones) which unconformably overlie the Coal Measures of the Alloa field are probably to be referred to the same group.

### (2) Productive Coal Measures.[2]

This group consists of white and yellow sandstones, sandy shales (fakes), dark-blue or black shales (blaes), and fireclays, intercalated in which are a number of valuable coals; blackband and clayband ironstones also occur. The group is estuarine or freshwater in origin, no marine horizon being known between the base and Skipsey's Band at the top. The characteristic fossil-beds here are the various "musselbands," containing lamelli-branchs belonging to the genera *Anthracomya*, *Carbonicola* and *Naiadites*; sometimes the shells occur in such profusion as to form a compact layer or 'lumachelle' (e.g. Cambuslang Marble,

[1] E. B. Bailey, 'Subterraneous Penetration by a Desert Climate,' *Geol. Mag.*, vol. lxiii, 1926, pp. 276-280. Another view interprets the colouration as due to staining by solutions penetrating downwards from the overlying New Red Sandstone. *See* for example J. G. Goodchild, 'Desert Conditions in Britain,' *Trans., Edinb. Geol. Soc.*, vol. vii, part iii, 1897, p. 219.

[2] Mining people sometimes refer to this group as the "Upper Coal Group," in contradistinction to the Lower (or Limestone Coal) Group.

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Kiltongue Musselband, etc.). *Spirorbis* is occasionally found. There is a rich flora, and the fish fauna is essentially estuarine in character. Remains of amphibia (*Anthracosaurus* and *Loxomma*) have been obtained at several horizons. A typical lithological sequence in the rocks of this group shows:—

Sandstone
Blue-black shales with clayband nodules.
Shales with *Carbonicola*.
Black fissile shale with plant remains.
Coal.
Fireclay with rootlets.
Sandstone.

The recurring cycles of deposition are incomplete in so far as they show no evidence of marine conditions. The fireclay and coal indicate an old surface, and the depression that followed converted the area into shallow-water mud-flats; accumulation of sediment then went on until a land surface was once more formed.

### (3) Millstone Grit.

This series of rocks consists mainly of sandstones, sometimes coarse-grained or pebbly, shales, fireclays and some impersistent thin coals; over much of North Ayrshire it is represented, largely or wholly, by contemporaneous volcanic rocks. It is the source of the valuable refractory fireclays and ganisters worked in Scotland (Glenboig, Castlecary, etc.),[1] while the well-known Ayrshire Bauxitic Clay, overlying the lavas and resulting from their weathering and decomposition, forms a local upper limit to the Series. Where most fully developed in the Central Coalfield (northern edge of Sheet 31) marine fossils have been recorded in it at at least six horizons (p. 528). The most persistent and widespread of these is the " Roman Cement " Limestone near the base, formed typically of crushed and flattened Orthotetid shells (*Derbyia* species). Indeed the lower part of the Millstone Grit is linked lithologically with the Upper Limestone Group and the conditions of deposition appear to have been similar.

### (4) Upper Limestone Group.

This group includes the strata between the top of the Castlecary Limestone and the base of the Index; in some areas the Castlecary is absent (*see* p. 462) and an arbitrary line has to be taken as the upper limit. The group is essentially arenaceous in character, with some thick beds of shales, four or five marine limestone

[1] *See* Fig. 8.

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bands and a few, generally thin, coals. The individual limestones in Fife, Midlothian and the Central Coalfield vary, as a rule, from 2 to 7 ft., and rarely exceed 10 ft., while the combined thickness averages between 20 and 30 ft. The shales overlying them often provide abundant fossil material, and in addition marine bands have been recorded from at least four other horizons. In Ayrshire individual limestones locally attain thicknesses of 25 or 30 ft. and the proportion of calcareous material to other sediments is much greater (*see* p. 530).

(5) LIMESTONE COAL GROUP.

This group, extending from the base of the Index to the top of the Top Hosie Limestone, consists of an alternating series of grey or yellowish sandstones, dark shales, fireclays, coals and ironstones It is the second great repository of workable coals. When traced throughout the coalfields it shows great variations in thickness while the number and thickness of the coals themselves also vary much from place to place. In the Midlothian coalfield, for example, this group, where most fully developed, contains 26 seams of coal over a foot thick. In some areas again there is not a single seam of economic importance, and indeed in Central Ayrshire the thickness of the whole Carboniferous Limestone Series has been shown to be locally as little as 96 ft. Few marine beds occur; the most important is the horizon known as the Johnstone Shell-bed (p. 524) which lies low down in the group not far above the Top Hosie Limestone. Marine fossils have also been obtained at at least one horizon between this and the thick series of shales known as the " Black Metals," and are found also in the " Black Metals " themselves. Deposited under conditions similar in the main to those of the Productive Coal Measures, the Limestone Coal Group also shows in its lower portion recurring phases of depression during which certain marine forms were able to flourish, although true limestones were rarely formed.

(6) LOWER LIMESTONE GROUP.

This group consists mainly of shales and limestones, although a certain proportion of arenaceous beds is usually present in addition. Certain of the limestones are locally as much as 60 ft. thick and the proportion of calcareous rock to the total thickness of the group is much greater than in the case of the Upper Limestones (*see* p. 530). A few coals are present, but only occasionally do they reach a workable thickness: e.g. Lillie's Shale-Coal of the Paisley district (one-inch Sheet 30) and the North Greens and Vexhim Coals of Midlothian.

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In the Lower, as well as in the Upper, Limestone Group, completed sedimentary cycles recur at many horizons. A full sequence shows:—

Sandstone
Shales, with clayband nodules
Shales, with *Lingula*
Calcareous shales, with a marine fauna
Limestone
Shales, with a marine fauna, chiefly lamellibranchs
Shales with *Lingula* and fish remains
Fissile shales with plant remains
Coal
Sandstone

This succession of beds should be compared with that given above for the Productive Coal Measures. It will be seen that the depression which carried the old land surface downwards was sufficient to allow of the establishment of clear-water conditions over the area; then followed a stationary phase when renewed sedimentation filled up the shallow sea and finally gave rise again to a new cycle.

### (7) Calciferous Sandstone Series.

This Series is subdivided into (a) a lower group of sediments, the Cementstone Group, passing downwards into strata that are referred to the Upper Old Red Sandstone; and (b) an upper, usually much thicker, group which contains in the Lothians a number of valuable oil-shales, and is, for this reason, often known as the Oil-Shale Group. The occurrence of oil-shales is, however, a purely local phenomenon. Both groups vary very much in thickness and in type of sedimentation. The upper group, for example, bears evidence of accumulation in more or less separate areas each with its own special conditions of deposition, and there is no general descriptive term that can be applied to it as a whole.[1] Over large tracts it is largely or almost wholly replaced by contemporaneous volcanic rocks. The following table shows the broad correlations that can be established within this very variable series of rocks:—

[1] The term "Calciferous Sandstone Series," as used originally by MacLaren in his 'Geology of Fife and the Lothians' (1839) included the Lower Limestone Group, the Calciferous Sandstone Series of present day nomenclature, and part also of the Upper Old Red Sandstone.



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CALCIFEROUS SANDSTONE SERIES.

| West of Scotland | East Fife | Midlothian | East Lothian | | North Northumberland |
|---|---|---|---|---|---|
| | | | North Berwick and Garleton | Dunbar district | |
| Upper Sedimentary Group (Erosion & overlap) | Rapid alternations of sandstones, shales, cement limestones, thin coals and fireclays; marine bands near top and base of Series | Sandstones, marls, shales, thin coals, and a number of workable oil-shales; several marine bands also occur | Upper Sedimentary Group (Erosion & overlap) | Upper part not well known. Calciferous Group with the Cove Limestones Carbonaceous Group (thin coals) Kip Carle Sandstone (Lower part of sequence not known) | "Lower Limestone Group" with the Woodend and Dun Limestones |
| Volcanic Rocks of the Clyde Plateau | | Arthur's Seat Lavas | Volcanic Rocks of Garleton Hills | | Scremerston Coal Group |
| | | | | | Fell Sandstone |
| ← | Cementstone | | Group | | → |

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(a) *Cementstone Group.* The most characteristic feature of this group in the Midland Valley is the rapid alternation of shales, sometimes grey or blue-black in colour, sometimes tinged a greenish or purplish hue, and thin cementstone ribs, with occasional bands of marly micaceous sandstone. This type of sedimentation is well seen at Ballagan of Strathblane in the Campsie district (Sheet 30) and is often referred to as the Ballagan type. Here about 600 feet of such sediments are exposed, and at the base occurs a passage zone into the sandstones of the Upper Old Red. The Group is not so well developed elsewhere in the Campsie district, and in the Garrel Burn, for example, N.N.W., of Kilsyth (Sheet 31), its position is occupied by volcanic rocks. The same relationship may hold in Sheet 39 where, between Gargunnock and Stirling, the volcanic rocks apparently overlap the Cementstones and come close to the Old Red Sandstone floor. Farther east, the group is again exposed in the River Devon, near Dollar,[1] but cannot be definitely recognised beyond the Georgetown Burn on the north side of the Cleish Hills (Sheet 40). In the Edinburgh district again the Cementstone group shows variegated shales and cementstone bands, with some sandstone, and occasional dark calcareous shales containing plant and fish remains and ostracods. Similar rock-types constitute the group in Renfrewshire and Ayrshire, and good sections can be studied in the country west and south of Loch Thom (Sheets 29, 30), in the Cessnock Water and Killoch Burn in the south part of Sheet 22, and at various localities farther south, e.g. at the Heads of Ayr, in the country north and east of Sorn, at Muirkirk, in Meikleholm Glen near Patna, in the Lindsayston Burn near Dailly (all in Sheet 14)[2], and elsewhere. Organic remains are rare, and the fossils most generally met with are plant and fish-remains, entomostraca and ostracods (*Leperditia*, etc.); the crustacea are also represented. The following occurrences may be noted:—

(1) At Heads of Ayr: *Lingula mytiloides* J. Sow., *Estheria striata* (Münster), *Anthracomya minima* (Ludwig), fish-remains.

(2) At Dailly: *Anthracomya minima*.

[1] It is at least 210 ft. thick here.

[2] The following thicknesses, recorded in borings, may be noted: 1 mile south-east of Patna, probably over 500 ft.; 3 miles south-east of Ayr, at least 330 feet.

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(3) Killoch Burn: *Estheria striata* var. *tateana* Jones, *Anthracomya minima*, *Spirorbis*, ostracods and fish-remains.

Rocks of Ballagan type again cover a considerable tract in Berwickshire where they have yielded remains of crustacea, myriapods and scorpions, in addition to fish-scales and well-preserved plants. The group corresponds to the lower division of the Tuedian of North Northumberland (at least 1500 feet thick) and as it is followed south-westwards towards Rothbury marine limestones make their appearance in the upper beds. In Liddisdale the group is represented by alternating estuarine and marine deposits, with clear-water limestones (containing *Lithostrotion*, etc.) towards the top. In Cumberland again, as in Liddisdale, the strata are more marine in character than in Northumberland and it seems reasonable to conclude that the Cementstone Group of these districts was laid down in an estuary or gulf with open sea to the south-west and land to the north-east (*cf.* p. 477). The Liddisdale facies points to deposition along the shores of the gulf mainly under estuarine conditions, but with prolonged periods during which the sea was able to invade and cover the mud-flats.[1]

The Cementstone Group of the Midland Valley on the other hand (Ballagan type) appears to have been laid down in inland lagoons or sheets of water more or less separated from one another by barriers of older rocks. The following points should be noted:

(1) The rhythmical alternation of shales and cementstones (essentially argillaceous dolomites) suggests periodic dessication of shallow lagoonal waters with precipitation of the dissolved salts.[2] Layers of gypsum have been recorded at several localities.

(2) The flaggy sandstones often show ripple-marked and sun-cracked surfaces while the occurrence of bands showing clay-galls or rounded fragments of cementstone also point to periodic dessication.

(3) The generally unfossiliferous character of the beds and the occasional presence of remains of land animals (myriapods and scorpions) indicate deposition in close proximity to land.

(4) The Cementstone Group passes conformably downwards

[1] *Cf.* Peach and Horne, 'The Canonbie Coalfield,' *Trans. Roy. Soc. Edinb.*, vol. xl, part iv, 1903, pp. 841-842.

[2] *See* J. Young, 'On the Geology of the Campsie District,' *Trans. Geol. Soc. Glasg.*, vol. i, part i, 1860, pp. 17, 18; 1868, p. 27; 1893, p. 31.

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into the Upper Old Red Sandstone and there is sometimes a passage zone linking the Lower Carboniferous rocks with the red and yellow pebbly sandstones, marls, and cornstones characteristic of the Upper Old Red. The sediments of the Cementstone Group in the Midland Valley indicate that the continental conditions (with large inland sheets of water) under which the Old Red Sandstone was accumulated persisted to some extent throughout this region into early Carboniferous times. The base of the Carboniferous is drawn where the Ballagan type of sedimentation makes its first appearance above the sandstones, marls and cornstones of the Upper Old Red, but in many sections it is very difficult, in the absence of definite fossil evidence,[1] to decide where the line should actually be drawn. Passage beds between the two formations have been recorded at a number of localities[2] and Mr. W. Q. Kennedy[3] has recently noted along the shore between Gourock and the Cloch Point (Sheet 30) examples of interbanding of Upper Old Red and Cementstone rock-types. In the Dailly district of South Ayrshire again Mr. J. E. Richey[4] has found evidence for the recurrence of typical Upper Old Red Sandstone conditions at the top of the Cementstone Group.

(5) Locally the Cementstone Group is missing and the volcanic rocks rest directly or almost directly on strata referred to the Upper Old Red Sandstone. Examples of this are to be found in the country lying between Ardrossan and Fairlie (Sheet 22), in the Kilsyth and Stirling districts (*see* p. 491), and in the country around Carnwath (Sheets 24, 23).

The East Lothian development of the Cementstone Group again has a somewhat different facies. In the North Berwick area, for example, there is a good deal of reddish sandstone and marl sometimes mixed with ashy material. Ash beds and shales with a few thin unfossiliferous limestones also occur. Pseudo-agglomerates consisting of angular or sub-angular fragments of the local

[1] Such as the scales or teeth of characteristic Upper Old Red fishes e.g. *Holoptychius nobilissimus*, *Bothriolepis major*, etc.

[2] *See*, for example, Peach and Horne, 'The Canonbie Coalfield,' *Trans. Roy. Soc. Edinb.*, vol. xl, part iv, 1903, p. 841; E. B. Bailey *in* 'Geology of the Glasgow District,' Mem. Geol. Surv. 1925, p. 11; A. G. MacGregor *in* 'Summary of Progress for 1922,' Mem. Geol. Surv., 1923, p. 79; J. E. Richey *in* Summary of Progress for 1924,' *Mem. Geol. Surv.*, 1925, p. 90.

[3] 'Summary of Progress for 1929, Part 1,' *Mem. Geol. Surv.*, 1930, p. 73.

[4] 'Summary of Progress for 1924,' *Mem. Geol. Surv.*, 1925, p. 91.

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rocks are present at several horizons and are considered[1] to represent portions of the banks of stream-courses torn off during floods, carried away by the mud-charged water and deposited with little or no sign of attrition as an irregular layer when the muds settled. The occurrence of blocks of marl in a marly matrix yield a type of boulder-bed which suggests formation under arid or semi-arid conditions with infrequent but torrential floods.[2] The boulders in the ash beds include fragments of marl, calcareous mudstone, green ash and lava and the larger ash blocks contain clastic micas, etc., mixed with the pyro-clastic material. They are not therefore the direct product of volcanic action but resemble rather the compound clastic and pyroclastic pebbles in the volcanic detrital beds which so often overlie the Clyde Plateau lavas. In the country between Dunbar and Cockburnspath the Cementstone Group consists largely of greenish or purple shales, thin unfossiliferous cementstones, and bands of greenish-grey sometimes calcareous sandstone, and resembles in general character the beds of the same age on Tweedside.

The picture we thus gather of the physiographic conditions under which the Cementstone Group of the Midland Valley was formed is that of the fringe of a continental area before its submergence under the waters of the Carboniferous sea. It held a series of lagoons or sheets of brackish water separated by land-barriers of older rocks and subject to periodic dessication; locally these lagoons allowed estuarine "mussels" (*Anthracomya*) and even *Lingula* to establish themselves. The climate was arid or semi-arid with infrequent but torrential rains which renewed and extended the waters of the lagoons and cut temporary outflows to the sea.

*Upper Calciferous Sandstone Group* (*Oil-Shale Group*). The Oil-Shale Group of the Lothians is characterised by a special type of sedimentation developed over a restricted area which includes West Lothian and part of Midlothian, and extends across the Firth of Forth into the Inverkeithing and Burntisland district of Fife. This area was very largely surrounded by land masses formed of Calciferous Sandstone volcanic rocks or of earlier formations (Old Red Sandstone). Alternating estuarine and lagoonal conditions prevailed during the deposition of the

[1] G. Barrow *in* 'Geology of East Lothian,' *Mem. Geol. Surv.*, 1910, p. 65.
[2] G. Barrow, *loc. cit.*, p. 61.

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greater part of the sediments. " The whole group is clearly of shallow-water origin, and was deposited over an area marked by intermittent subsidence of irregular amount, where incursions of the open sea were extremely rare. Much of the sediments must have accumulated under mud-flat conditions, for sun-cracks and ' dessiccation-breccias ' are commonly met with, especially in the marly strata that bulk so largely in the series."[1] The thick beds of marl which characterise the upper part of the Group (*cf.* p. 514) are difficult to account for, but probably represent the finer waste of the neighbouring volcanic plateaus.[2] The Oil-Shale Group thins away rapidly as it is followed northwards into Fife, north-eastwards into the Blackness district, and south-westwards into the Tarbrax and Braehead country. Not only do the shales themselves deteriorate in these directions but there is marked attenuation of the strata accompanied by a change in lithological facies indicating the proximity of contemporaneous shore-lines. To the west and north-west lay the great Clyde volcanic plateau; to the east the volcanic region of the Garleton Hills; while to the south-west the lower Old Red Sandstone rocks of the Lanark-Lesmahagow ridge must have persisted as a land-barrier until near the close of Calciferous Sandstone times.

Rocks of the same age cover a large area in East Fife and extend from near St. Monans round the coast past Crail and Fife Ness to St. Andrews. The Calciferous Sandstone of this area is roughly 4,000 feet thick and consists of a rapidly alternating series of sandstones, shales, thin coals, fireclays, ironstones, thin limestones and shelly bands. Of the 761 different beds enumerated by Kirkby[3] only about 10 exceed 30 feet in thickness. Richly fossiliferous marine bands occur at 10 different horizons and when compared with the Oil-Shale Series of the Lothians the Calciferous Sandstone of East Fife clearly shows that this area was subject to more frequent and more prolonged incursions of the sea. A detailed study of the marine bands of the two regions may yet allow of closer comparison than has hitherto been possible. It seems probable that the Billowness Sandstone near the base of the East Fife succession is represented by the Granton Sandstone

[1] R. G. Carruthers *in* ' Oil Shales of the Lothians,' *Mem. Geol. Surv.*, 3rd ed., 1927, pp. 3-4.

[2] *Cf.* B. N. Peach, ' Some Points in the Natural History of the Carboniferous Period in East Scotland,' *Proc. Roy. Phys. Soc. Edinb.*, vol. xix, 1916, p. 247.

[3] J. W. Kirkby *in* ' Geology of East Fife,' *Mem. Geol. Surv.*, 1902, pp. 77-99.

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of the Lothians and by part of the Fell Sandstone group of the Borders.

In the Dunbar-Cockburnspath district of East Lothian again a rough three-fold division can be established on the coast at Cove, but much of the Series must be cut out by the Cove fault. The divisions (from above downwards) are:—

(3) *Calciferous Group*, including the thick sandstones of Heathery Heugh, Cove Harbour and Bilsdean, and the Lower and Upper Cove Limestones.[1] The beds exposed are 516 feet in thickness but between the top of the group and the base of the Carboniferous Limestone Series there are probably several hundred feet more of strata.[2]

(2) *Carbonaceous Group*, 85 ft. or so in thickness, and consisting of shales, sandstones and a few thin coals and ironstones.

(1) *Kip Carle Sandstone*, about 50 feet thick, against the Cove fault.

Group (3) corresponds to the lower part of the " Lower Limestone Group " of Northumberland (*see* Plate IV); groups (2) and (1) to part of the Scremerston Coal Group.[3]

Along the southern margin of Sheet 22 and northern part of Sheet 14, where the Volcanic Group of North Ayrshire dies out (*cf.* p. 450) the Calciferous Sandstone shows a two-fold division into:—

Upper Calciferous Sandstone Group
Lower or Cementstone Group.

The Cementstone Group is as a rule much the thicker and contains locally at or near the top a thin development of volcanic rocks. The Upper Group is mainly an arenaceous series with some shales, fireclays, thin coals and two or three marine limestones. Farther south it shows a somewhat different facies and Mr. J. E. Richey[4] has found in the Dailly field evidence for a recurrence of Upper Old Red Sandstone conditions during part of the interval between the Cementstone Group and the Lower Limestones (sandstones, conglomerates and marls with cornstone concretions). This peculiar type of Upper Calciferous Sandstone sedimentation

[1] Tentatively correlated with the Dun and Woodend Limestones of Northumberland (*see* ' Geology of East Lothian,' *Mem. Geol. Surv.*, 1910, p. 46).

[2] *Loc. cit.*

[3] Possibly the Kip Carle Rock is the equivalent of the highest part of the Fell Sandstone.

[4] ' Summary of Progress for 1924,' *Mem. Geol. Surv.*, 1925, p. 91.

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extends northwards in Sheet 14 as far as Loch Martnaham but dies out in the direction of Ayr. The same phenomenon is seen also on the south-east side of the Muirkirk basin.

Reference to the Table on p. 490 will show that contemporaneous igneous rocks are, in certain districts, associated with the Calciferous Sandstone Series, and are sometimes in great excess over the sediments. In such cases the development is as follows:—

Upper Sedimentary Group.
Volcanic Group.
Cementstone Group.

*Volcanic Group.* This group attains its greatest development in the West of Scotland where it covers wide tracts of country on both sides of the River Clyde. It forms the terraced plateaus of the Kilpatrick and Campsie Hills on the north side of the river where the total thickness of igneous rocks may be as much as 3,000 feet; it underlies the Carboniferous sediments of the Glasgow-Paisley district and builds up the broad volcanic platform of the Renfrewshire-North Ayrshire uplands. Volcanic activity, it is clear, commenced earlier in certain areas and the igneous rocks may locally rest directly or almost directly on the Upper Old Red Sandstone (p. 491). Eastwards the volcanic group can be traced into the Stirling (Sheet 39) and Strathaven (Sheet 23) districts and must have formed in early Carboniferous times a continuous platform extending from Kintyre and Arran through North Ayrshire and Renfrewshire as far east as Stirling. In Ayrshire again the group dies out southwards towards Ardrossan and Galston.

In the East of Scotland volcanic activity was not so pronounced, but in the North Berwick-Garleton area it continued until well on in Upper Calciferous Sandstone times. The Series in this area shows the same three-fold division as obtains in the West of Scotland:—

Upper Sedimentary Group.
Volcanic Group (Garleton Hills).
Lower Sedimentary Group (*see* p. 493).

On the north shores of the Firth of Forth, between Burntisland and Seafield, the sediments above the Houston Coal are largely replaced by lavas and tuffs.

Volcanoes were also active in the Midlothian area towards the close of Cementstone Group times and their lavas and ashes

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build up Arthur's Seat and the Calton and Craiglockhart Hills in the Edinburgh district; volcanic rocks of approximately the same age are found also in the Corston Hill area, 2½ miles south of Mid Calder (Sheet 32; north-west of the Pentland Hills), have been proved in the deep boring for oil put down in 1919-21 at West Calder,[1] and can be traced south-westwards into the Tarbrax (Sheet 24) and Carnwath (Sheet 23) districts.[2] They die away westwards against the old ridge of Lower Old Red Sandstone rocks to the east and south-east of Carluke (Sheet 23).

A thin development of volcanic rocks overlying sediments of Cementstone Group age occurs about four miles east of Dollar on the north slopes of the Cleish Hills (Sheet 40). These may perhaps represent an extension of the Clyde Plateau lavas.

*Upper Sedimentary Group.* The strata included here occupy the interval between the top of the Volcanic Group and the base of the Carboniferous Limestone Series. They rest with a pronounced overlap on the older rocks, and it is clear that prolonged erosion of the lavas must have preceded their deposition. The first sediments to be laid down were derived directly from the weathering and degradation of the lavas themselves and are known as the *basal volcanic detritus*. This deposit consists essentially of reddish and greenish marl resembling a fine-grained tuff but containing in its disseminated micas and quartz grains, in its layers of water-worn lava-pebbles, and in its association with normal sediments at widely-different stratigraphical levels clear evidence of a detrital origin. Denudation of the lavas must have been widespread and prolonged but we have no way of estimating how much of them may have actually been removed.[3]

The basal detritus fringes and underlies the basins in which the higher Calciferous Sandstone sediments were laid down. These vary a great deal in character and thickness; they include, for example, in the West of Scotland such dissimilar rock-groups as the marls and thick coals of the Paisley area, the coarse quartzose conglomerates of the Kilpatrick and Campsie districts (Craigmaddie Muir Sandstones), the very attenuated sequence of ashy beds, shales and coral limestones of the Corrie and Stirling districts, and

[1] The volcanic rocks proved in this bore are probably of somewhat later age than those of Arthur's Seat.

[2] They form here the local base of the Calciferous Sandstone Series.

[3] *See*, for example, J. E. Richey, *in* 'Geology of North Ayrshire,' *Mem. Geol. Surv.*, 1930, p. 64.

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the greenish marls, thin coals and shell-beds of Strathaven. Detailed lithological sequences cannot be established between one area and another while the marine horizons show marked faunal differences (*cf.* p. 518). There is evidence also for minor unconformities in these strata and for lateral and comparatively rapid variation. The Upper Sedimentary Group in the Beith district of North Ayrshire (Sheet 22), for example, has a thickness of only 225 ft. or so as compared with the thickness of about 1100 ft. found at Paisley (Sheet 30). The Broadstone Limestone of North Ayrshire can be correlated with the Blackbyre Limestone of Paisley[1] but below this horizon only tentative correspondences can be made. These variations in amount and character of the sediments point to accumulation in more or less isolated areas of deposition or along the course of an estuary where changes in sedimentation were constantly occuring. On the margins of these areas the strata terminate against the land-barriers of older rocks. Differential crustal movements must have played an important part in the determination of the land and sea areas of the period and clearly indicate an early stage in the submergence which finally carried so much of the Midland Valley beneath the waters of the Carboniferous Limestone Sea (Hurlet Limestone transgression). Submergence however took place irregularly and the land-barriers of late Calciferous Sandstone times persisted as relatively "stable" areas, that is as areas over which crustal depression was less than in others. To this division into "stable" and "unstable" areas appear to be due, in a large measure, the great differences in thickness shown by the later subdivisions of the Carboniferous rocks.

Along the southern edge of the Central Coalfield also, the Upper Sedimentary Group shows great variations. The sequence found above the old lava plateau at Strathaven amounts to about 420 ft., but westwards the overlap increases and in the western part of the East Kilbride basin (Sheet 33) the lowest limestone of the Carboniferous Limestone Series is underlain directly by volcanic detritus. At Lesmahagow again only a few feet of Calciferous Sandstone sediments are present above the lavas. At Carluke the Calciferous Sandstone overlaps on to the Lower Old Red Sandstone, but farther east in the Carnwath

[1] Fig. 7. *See* R. G. Carruthers and J. E. Richey, 'The Lower Limestones of Renfrewshire and North Ayrshire,' *Trans. Geol. Soc., Glasgow*, vol. xiv, part iii, 1913, pp. 309-322.

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country the lavas reappear and can be followed north-eastwards towards the Pentland Hills (Sheets 24 and 32).

The Upper Sedimentary Group is found also in the Gullane and Haddington areas (Sheet 33) above the pile of volcanic rocks which build up the Garleton Hills. The sequence is not however well-known but includes sandstones, variegated marly fireclays, a few thin coals and occasional marine horizons (e.g. Lennoxlove and Sandersdean limestones). Here again the sediments, with a marked band of volcanic detritus at the base, rest unconformably, and with a pronounced overlap, on the lavas.

Neither Cementstone Group nor Volcanic Group have been found along the north-eastern fringes of the Fife Coalfield and the Calciferous Sandstone strata present, referable to the upper part of the Series, rest on the Upper Old Red Sandstone floor. These strata are seen on the west side of the Lomond Hills and can be followed along the northern face of the hills and thence north-eastwards by Kettlehill and Bridgend (Sheet 40). They are poorly developed at the western end of the outcrop but thicken eastwards. To the south of Loch Leven the Volcanic Group makes its appearance and farther west still the tripartite division (Cementstone Group, Volcanic Group, Upper Sedimentary Group) characteristic of the West of Scotland is found. We know very little of the development of the Calciferous Sandstone underneath the Carboniferous Limestone areas of West and Central Fife, but the beds exposed to the west of Loch Fitty, and others proved in a few borings, must be referred to the highest part of the Series. Farther south again in the Burntisland district on the shores of the Firth of Forth we reach an area where strata characteristic of the Oil-Shale Group of the Lothians are well-developed (p. 494).

## V. DISTRIBUTION OF ROCK TYPES.

The succession outlined above is built up mainly of sandstones, shales, and rock-types intermediate in character between these, i.e. shaly sandstones (or fakes) and sandy shales (or faky blaes). Subordinate to these are the limestones, coals, fireclays, marls, ironstones and oil-shales. It is important to note the vertical distribution of these different rock-types and the relative proportions in which they occur. Accordingly a typical area of Carboniferous rocks has been selected and a series of diagrams prepared to illustrate this point. The area selected is the

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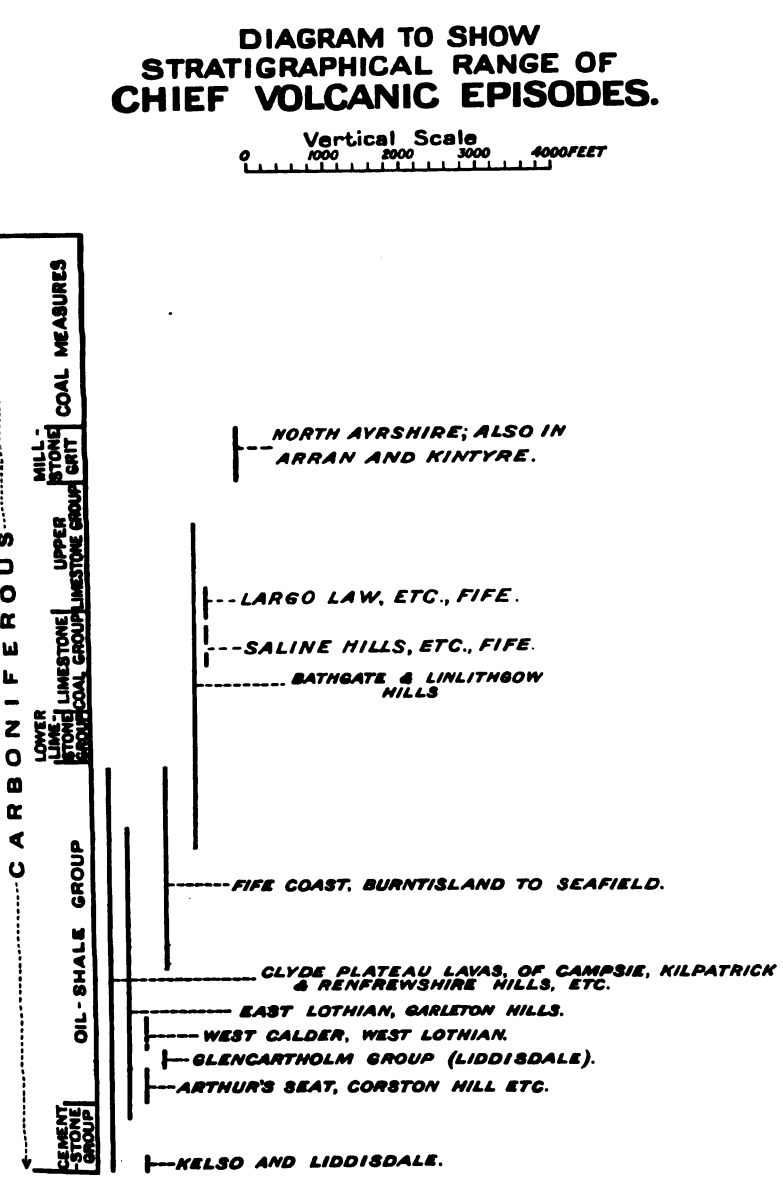


FIG. 4.

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Central Coalfield[1] and the diagrams show the distribution of the following:—

(1) Arenaceous strata (sandstones, faky sandstones and fakes). Fig. 5.
(2) Shales, ironstones and marls. Fig. 6.
(3) Limestones and shell-beds. Fig. 7.
(4) Coals, oil-shales and fireclays. Fig. 8.

The succession has been carried down to the top of the Calciferous Sandstone lavas in the Paisley district and a section of the Oil-Shale Group of the Lothians added. In order to make the series more complete a diagram (Fig. 4) showing the stratigraphical range of the chief volcanic episodes in the Scottish Carboniferous has also been prepared.

*Contemporaneous Volcanic Rocks.* Lavas and ashes, poured out, or ejected, from volcanoes that were active in Carboniferous times, form locally a considerable part of the sequence. In the following diagram, Fig 4, an attempt has been made to show the principal volcanic episodes and to indicate their stratigraphical range. It will be seen that the most prolonged and widespread manifestations of volcanic activity occurred in pre-Carboniferous Limestone times. A brief account of the distribution of the volcanic rocks of Calciferous Sandstone age has already been given in the section dealing with that subdivision (pp. 497 to 498). The volcanic eruptions which produced the lavas and ashes of the Bathgate-Linlithgow Hills began in late Oil-Shale times.[2] and continued throughout the greater part of Carboniferous Limestone times. In this region igneous rocks form nearly the whole of the Carboniferous Limestone Series up to or almost up to the horizon of the Calmy Limestone; they die away northwards and southwards while westwards they must extend under the cover of later sediments, although how far and in what force it is impossible to say. That buried volcanic centres are concealed underneath the Millstone Grit and Coal Measures on the north-east side of the Central Coalfield (Sheet 31) has been proved by borings in recent years; a boring on Balmuir farm, three-quarters of a mile south-

[1] The Central Coalfield includes the whole of one-inch Sheet 31, the eastern part of Sheet 30, the northern part of Sheet 23 and small portions of Sheets 22, 24, 32 and 39. The whole of the Lanarkshire Basin falls within it.

[2] The ash bed above the Two Foot Coal in the north-west part of the main Lothians Shale-field (Ecclesmachan, Philipstoun, etc.), marks an early stage in these eruptions.

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east of Westfield Station (Linlithgow 5 S.W.) entered volcanic rocks 33½ fms. below the Levenseat Limestone and proved no less than 188½ fms. of lavas, ashes and agglomerates before it was stopped.[1]

The volcanic rocks of the Saline Hills area of West Fife are of late Limestone Coal Group age; evidence of volcanic activity during the deposition of the upper part of the Limestone Coal Group has also been obtained in recent years in the Lochore and Kirkcaldy districts.[2] D. Balsillie[3] has lately shown that the ashes and tuffs of the Largo Law neighbourhood are intercalated among strata belonging to the Upper Limestone Group.[4] Beds of volcanic ash occur also at several horizons in the Limestone Coal and Upper Limestone Groups of the country south-west of Dalry (North Ayrshire).[5]

(1) Distribution of Sandstones (Fig. 5).

The principal sandstone horizons are found in the Oil-Shale Group, Upper Limestone Group, Millstone Grit, and Coal Measures. The names of some of those that have furnished important supplies of building-stone or of moulding sand have been added to Fig. 5, but the list given is far from complete. As a rule the sandstones that occur in the Barren Red Measures are soft, rather coarse-grained, reddish rocks, blotched with streaks and spots of a deep red colour and often containing large irregular concretionary masses in which the sand grains are cemented by carbonate of lime; others again are lighter in colour or greyish and some have a greenish tinge. The sandstones of the Productive Measures are white or yellowish, in marked contradistinction to those of the Barren Group, and have a finer and more even grain. The change from one type to another does not, however, take place at any definite stratigraphical horizon and the red colouration

[1] M. Macgregor *in* 'Economic Geology Central Coalfield, Area VI,' *Mem. Geol. Surv.*, 1923, pp. 20 and 21; H. M. Cadell, 'A Volcano in the Bathgate Coalfield,' *Trans. Inst. Min. Engineers*, vol. lxv, 1923, pp. 251-259, and in 'Rocks of West Lothian,' 1925, ch. xviii.

[2] J. K. Allan in 'Summary of Progress for 1924,' *Mem. Geol. Surv.*, 1925, p. 114; J. Knox in 'Summary of Progress for 1925,' *Mem. Geol. Surv.*, 1926, p. 123.

[3] *Geol. Mag.*, 1923, pp. 530-542.

[4] Sir A. Geikie ('Ancient Volcanoes of Great Britain,' 1897, p. 283) considered that they rested unconformably on the Carboniferous sediments and assigned them to the Permian.

[5] 'Geology of N. Ayrshire,' *Mem. Geol. Surv.*, 1930, pp. 177-180.

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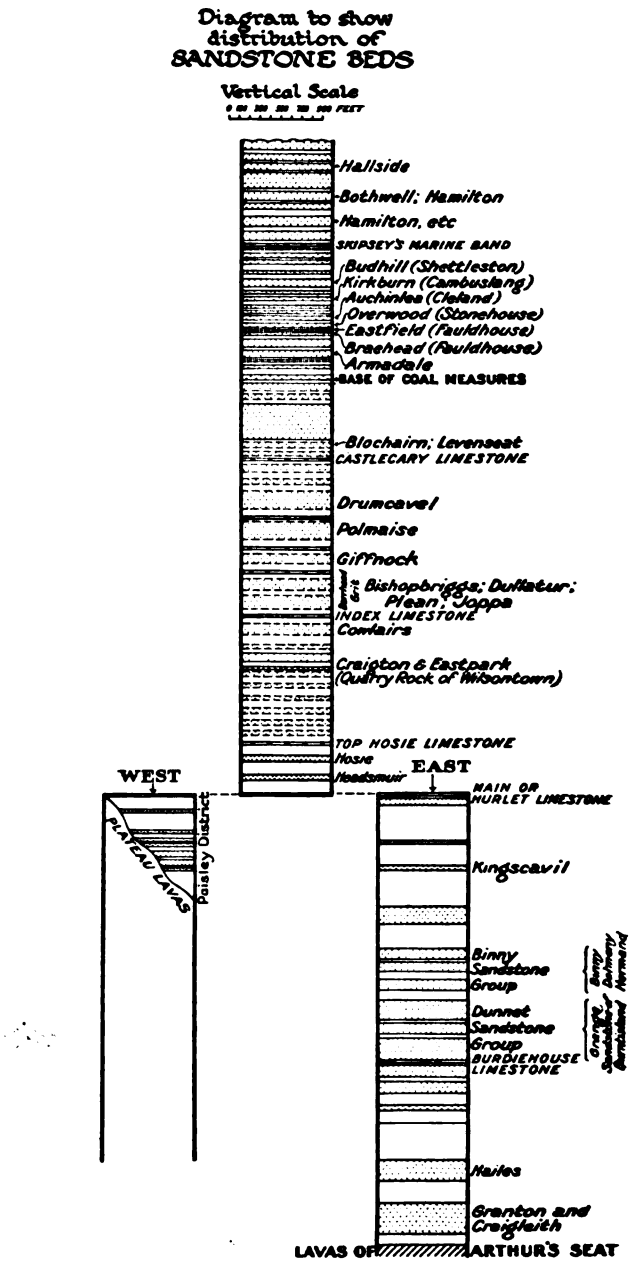


FIG. 5.

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characteristic of the Barren Group may be absent throughout the first 25 or 30 fms. above Skipsey's Marine Band; red sandstones are sometimes found, on the other hand, below it (*cf.* p. 485). The Millstone Grit is largely composed of somewhat massive, often current-bedded sandstones, varying a good deal in texture and colour; those of the Central Coalfield are in the main white and medium-grained, but coarse gritty bands are common; in Midlothian and Fife again the sandstones of this Series are dominantly coarse-grained with pebbly layers and conglomeratic bands (chiefly of quartz pebbles) and are very often reddish in colour, e.g. Roslin Sandstone of the Edinburgh district. Those of the Upper Limestone Group are light-coloured and, as a rule, fine-textured, although coarse and even pebbly bands occur, as in the Barrhead Grit of the Glasgow district or the Cadgers Loan rock of the Denny district. The sandstones of this group have proved a valuable source of freestone (*see* list below) but show rather rapid lateral variation, the workable stone often passing quickly into thin-bedded faky sandstone; some of them, containing a cement of kaolin or of mica in fine flaky aggregates, are in demand as moulding sand, e.g. Drumcavel. Sandstones again sometimes in thick beds, are characteristic of the upper part of the Limestone Coal Group (e.g. Cowlairs rock) and occur locally in the Lower Limestone Group (Hosie and Headsmuir sandstones). In the Oil-Shale Group of the Lothians there are the Binny, Dunnet, Hailes and Granton series of sandstones, greyish or white in colour, all of which have produced large quantities of building-stone for use in the Edinburgh district; the lowest of these, the Granton Sandstone, may be correlated with the Billowness Sandstone of the East Fife (Anstruther) coast and is probably represented by part at least of the Fell Sandstone of the Borders. The Craigmaddie Muir Sandstones of the Campsie-Kilpatrick districts (north of Glasgow, Sheet 30) form a purely local base to the Calciferous Sandstone sediments overlying the Clyde Plateau lavas and show quartzose conglomerates and grits passing upwards into sandstones of finer grain. Arenaceous strata bulk largely in the Calciferous Sandstone Series of East Lothian (Sheet 33), both in the Cementstone Group underlying the volcanic rocks and in the sediments (Oil-Shale Group) above them; to the latter belong the sandstones quarried at Gullane and at Rentonhall to the south-east of Haddington. Farther south-east in the Dunbar-Cockburnspath district the local Calciferous Sandstone sequence includes



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the Horse Roads Sandstone, intercalated near the base of the Cementstone Group, the Kip Carle Sandstone, perhaps representing part of the Fell Sandstone of Northumberland,[1] and the successively higher sandstone horizons of Heathery Heugh, Cove Harbour and Bilsdean.

For details regarding the important sandstones reference should be made to the various general and economic memoirs on the Scottish Carboniferous rocks published by the Geological Survey.[2] It may be of some interest to note here the exact stratigraphical horizon of these indicated in Fig. 5 along with the one-inch and six-inch Geological Survey Sheets in which the quarries referred to occur.

(a) Barren Red Measures. A number of quarries have, at one time or another, been opened in the reddish sandstones of this group in the Hamilton-Bothwell-Uddingston district. The rock quarried at Hallside (Sheet 31; Lanark 11 N.W.) lies about 170 fms. above the Ell Coal; the Bothwell Park quarries (Sheet 31; Lanark 11 N.E.), portions of which are said to be 200 years old, are in a lower sandstone, and the rock once quarried at Bredisholm is at a somewhat lower horizon still. A number of quarries have also been worked around Hamilton in sandstones belonging to this group. The Eastfield quarry stone (west of Cambuslang) is a reddish sandstone lying 40 fms. or so above the Ell Coal and it is not certain whether it actually falls within the Barren Red Measures (i.e. above Skipsey's Marine Band).

(b) Among quarried sandstones belonging to the Productive Coal Measures may be noted: Braehead, 12 miles east of Baillieston, between the Upper Coal and Skipsey's Band; Budhill,

[1] *See* p. 496. The Gifford Sandstone of the Haddington area is perhaps on the same horizon.

[2] *See also* J. Young, 'On some peculiar varieties of Old Red and Carboniferous Sandstones from the Neighbourhood of Glasgow,' *Trans. Geol. Soc. Glasgow*, vol. ii, part i, 1865, pp. 33-37; J. W. Young, 'On the Chemistry of some Carboniferous and Old Red Sandstones,' *Ibid.*, vol. ii, part iii, 1867, pp. 189-209; W. Wallace, 'On the Decay of Building Stones,' *Proc. Phil. Soc. Glasgow*, vol. xiv, 1883, pp. 22-31; J. Bennie, 'The Redemption of Sandstone Quarries,' *Trans. Geol. Soc. Glasgow*, vol. viii, part 2, 1888, pp. 298-307; P. Macnair, 'The Giffnock Sandstones, *Ibid.*, vol. xi, part 2, 1900, pp. 199-231; G. Craig, 'On the Building Stones used in Edinburgh,' *Trans. Edinb. Geol. Soc.*, vol. vi, part iv, 1892, pp. 254-273; W. R. Smellie, 'The Sandstones of the Upper Barren Red Measures to the East of Glasgow,' *Trans. Geol. Soc. Glasgow*, vol. xiv, part 3, 1913, pp. 258-278.

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Shettleston, 12 fms. above the Ell; Kirkburn, Cambuslang, above the Humph Coal; Auchinlea, near Cleland (Sheet 31; Lanark 12 N.E.), between the Virtuewell and Blackband coals; Overwood, near Stonehouse (Sheet 23; Lanark 24 S.W.), above the Kiltongue Musselband; Eastfield, Fauldhouse (Sheet 31; Linlithgow 12 S.W.), below the Kiltongue Musselband; Braehead and Fallahills, Fauldhouse (Sheet 31; Linlithgow 11 N.E.), above the Upper Drumgray or Furnace Coal; Barbauchlaw, Armadale (Sheet 31, Linlithgow 8 N.E.), above the Mill Coal; etc.

(c) Among the quarried sandstones of the Millstone Grit may be noted those of Germiston and Blochairn, near Glasgow, the material of which was ground down and used for moulding sand. The friable sandstone found above the 'Roman Cement Limestone' (p. 487) at Levenseat (Sheet 31; Edinburgh 10 S.E.) is crushed for use in foundries and in bottle-glass works. The 'ganisters' and 'silica rocks' mined for refractory purposes at Glenboig, Castlecary, etc. (Sheet 31), also belong to the Millstone Grit (Fig. 8).

(d) To the Upper Limestone Group belong: the sandstone of Drumcavel and Avenuehead quarries, near Chryston (Sheet 31; Lanark 2 S.E.), a little above the Calmy Limestone; the sandstone of Dunmore and Polmaise quarries (Sheet 39; Stirling 18 S.W.) beneath the Calmy Limestone; the Auchenheath quarry rock (Sheet 23, Lanark 24 S.E.), also beneath the Calmy Limestone; the Giffnock Sandstone (Sheet 30; Renfrew 13 S.W.), between the Orchard and Lyoncross limestones; and the Bishopbriggs Sandstone, above the Index Limestone. The Drumcavel Sandstone is ground for moulding purposes; the others referred to have all yielded important supplies of valuable building-stone. The Bishopsbriggs Sandstone was formerly wrought in the Huntershill, Coltpark and Kenmure quarries at Bishopbriggs (Sheet 31; Lanark 1 S.E.), and sandstone on the same horizon has been worked at Netherton (Sheet 30; Dumbarton 25 N.E.), at Queenziemill, 3 miles N.E. of Kirkintilloch (Sheet 31; Stirling 28 S.E.), at Plean (Sheet 31; Stirling 24 N.W.), and at other localities; to the south-west of Glasgow most of the interval between the Index and Lyoncross Limestones is occupied by somewhat coarse sandstones known as the Barrhead Grit and the Bishopbriggs Sandstone corresponds to the lower part of this arenaceous series.[1]

[1] The Cadgers Loan rock of Denny, referred to previously, is the equivalent of the upper part of the Barrhead Grit.

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(e) The Eastpark rock, once quarried on the north side of Glasgow (Lanark 6 N.W.), lies partly above, partly below the Knightswood Gas Coal. The Craigton Sandstone of the Govan district (Lanark 6 S.W.) is on the same horizon.

The Quarry Rock of Wilsontown (Sheet 23; Lanark 20 N.W.) lies a little below the Main Coal of that district, and a stone on the same horizon was worked to the south-east of Carluke (Sheet 23).

(f) The Binny Sandstone of the Oil-Shale Group of the Lothians occurs between the Broxburn and Dunnet Shales, the Dunnet Sandstone below the Dunnet Shales; the sandstones of Hailes and Granton lie much lower down near the base of the group. The Binny rock has been extensively quarried at Binny near Uphall (Sheet 32; Linl. 6 S.W.)[1] at Hermand (Edinburgh 11 N.W.),[2] at Dalmeny (Linlithgow 3 S.W.) and at Straiton (Edinburgh 7 S.E.). The Dunnet Sandstone has been largely wrought at Grange Quarry in the Burntisland district on the north side of the Firth of Forth (Fife 40 N.W.). The main quarries in the Hailes Sandstone were at Hailes and Redhall, and in the Granton Sandstone at Craigleith (said to have been worked as early as the beginning of the 17th century), at Craigcrook and at Ravelston; all these are in the Edinburgh meighbourhood. The Kingscavil Sandstone of the Philipstoun district (Sheet 31; Linlithgow 1 S.E.) lies near the top of the Oil-Shale Group.

For lists of important buildings constructed of stone from the various horizons listed above, reference should be made to "Geology of the Glasgow District" (*Mem. Geol. Surv.*), 1925, pp. 265-266, and to "Oil-Shales of the Lothians" (*Mem. Geol. Surv.*), 1927, p. 10. At present, and for some years past, very little building-stone has been quarried from Carboniferous sandstones in Scotland. This is due in part at least to the difficulty of finding a suitable stone. The Scottish Carboniferous sandstones do not often yield material that can be readily dressed into large blocks; they are too often split up irregularly by partings or bands of faky or shaly material, and even when good freestone posts occur they appear to be impersistent. They are often much broken up by joints, and many of them, especially those from the Lower Carboniferous, show traces of oil giving rise

[1] The Scott Monument, National Gallery and other important buildings in Edinburgh are built of stone from this quarry.

[2] The Royal Scottish Museum and the Calton Prison are largely built of this stone.

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to black patches on the surface of the stone when exposed to weathering.[1]

(2) DISTRIBUTION OF SHALES, IRONSTONES AND MARLS. (FIG. 6).

(a) *Shales.* Shales (mudstones) are most abundantly developed in the Cementstone Group, the Upper Oil-Shale Group of the Lothians, the Lower Limestone Group, and the lower part of the Limestone Coal Group. They are found also at many horizons in the other groups, notably above the limestones of the Upper Limestone Group. Very generally also the various coal seams are succeeded by a variable thickness of dark mudstones. The shales of the Barren Red Measures are, as a rule, mottled in appearance, showing pale-grey, lilac, brownish and reddish tints, and individual beds may reach locally a thickness of as much as 70 feet. Those of the Productive Coal Measures and of the Carboniferous Limestone Series are dark-coloured, generally soft and incoherent deposits, breaking readily in any direction and crumbling on exposure. In the latter series of rocks they have a characteristic dark-blue hue (hence the Scottish term blaes), but in the Productive Coal Measures are much darker and more charged with carbonaceous material. Some beds, e.g. the blaes above the Calmy and Orchard Limestones and the "Black Metals" in the middle of the Limestone Coal Group, have been proved to have a wide distribution and serve as useful index horizons for correlation purposes. A definite type of shale is represented by the more bituminous, harder, and fissile material known in Scottish mining parlance as shaly or parroty blaes, grading on the one hand into ordinary mudstones (blaes) and on the other into the canneloid shales and cannel[2] or gas coals. Some of these canneloid shales have been used for the production of oil (*see* Fig. 8) but the true oil-shales of the Lothians stand in a class by themselves (*see below*, p. 531). The mudstones grade upwards into sandy beds (faky blaes) showing a rapid alternation of argillaceous and arenaceous sediment. Surfaces displaying sun-cracks, and 'desiccation-breccias' formed of irregular pellets and balls of mud are not uncommon and indicate periods when the old mud-flats were exposed to rapid dessication under arid

[1] *See* D. Tait, 'On the Occurrence of Petroliferous Sandstones in the Carboniferous Rocks of Scotland and this Relation to certain Black Sandstones, *Trans., Edinb. Geol. Soc.*, vol. xii, part i, 1928, pp. 90-104.

[2] I.e. candle coal; also termed 'parrot coal' from the crackling noise made in burning.

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conditions; these phenomena are specially characteristic of the Oil-Shale Group. The rhythmic alternation of variegated mudstones and thin argillaceous limestones (cementstones), characterising the Cementstone Group suggests deposition in lagoons under recurring geographical conditions that give rise alternately to wet and dry periods (p. 492).

Most of the shales are barren of fossils except for scattered and indeterminate plant debris. Well-preserved plant and fish remains are locally abundant, however, in the shales overlying coal seams in both the Limestone Coal and Productive Coal Measures groups while the more or less calcareous shales overlying the various marine limestones have yielded rich supplies of valuable palaeontological material.

(b) *Ironstones.* A complete account of the Scottish ironstones is given in 'The Iron Ores of Scotland,'[1] The Carboniferous ores are bedded clayband and blackband ironstones, very irregular in their occurrence, and as a rule thin. The claybands are siderite-bearing mudstones composed of soluble ferrous carbonate (with some manganese and magnesium) and an insoluble basis of clay material. In origin they appear to represent the precipitates of warm inland lagoonal waters mixed with fine sedimentary material, and to indicate formation under wide-spread arid conditions. Many of the beds of shale throughout the Carboniferous succession contain balls or nodules of clayband which at certain horizons have proved numerous enough to repay extraction; in other cases again the ore is concentrated into thin ribs or lenticular bands. It was surface or shallow workings in nodules or ribs of this kind that laid the foundations of the iron industry of Scotland, during the period from 1760 to 1830, and any accessible exposure of shales containing these was considered worthy of exploitation in the early days when only small supplies could be dealt with; other sources were the balls or ribs overlying worked coals. The first blackband to be discovered was the Palacecraig seam found by Mushet in 1801 near Cairnhill Old Mill (Sheet 31; Lanark 8 S.W.), and this was followed by the discovery of the once famous Airdrie Blackband and the similar ores at Fauldhouse (Sheet 31), at Wilsontown (Sheet 23), at Cadder near Glasgow, and at other localities. It was not, however, until Neilson's introduction in 1828 of the hot blast in

[1] *Mem. Geol. Surv.*, 1920.

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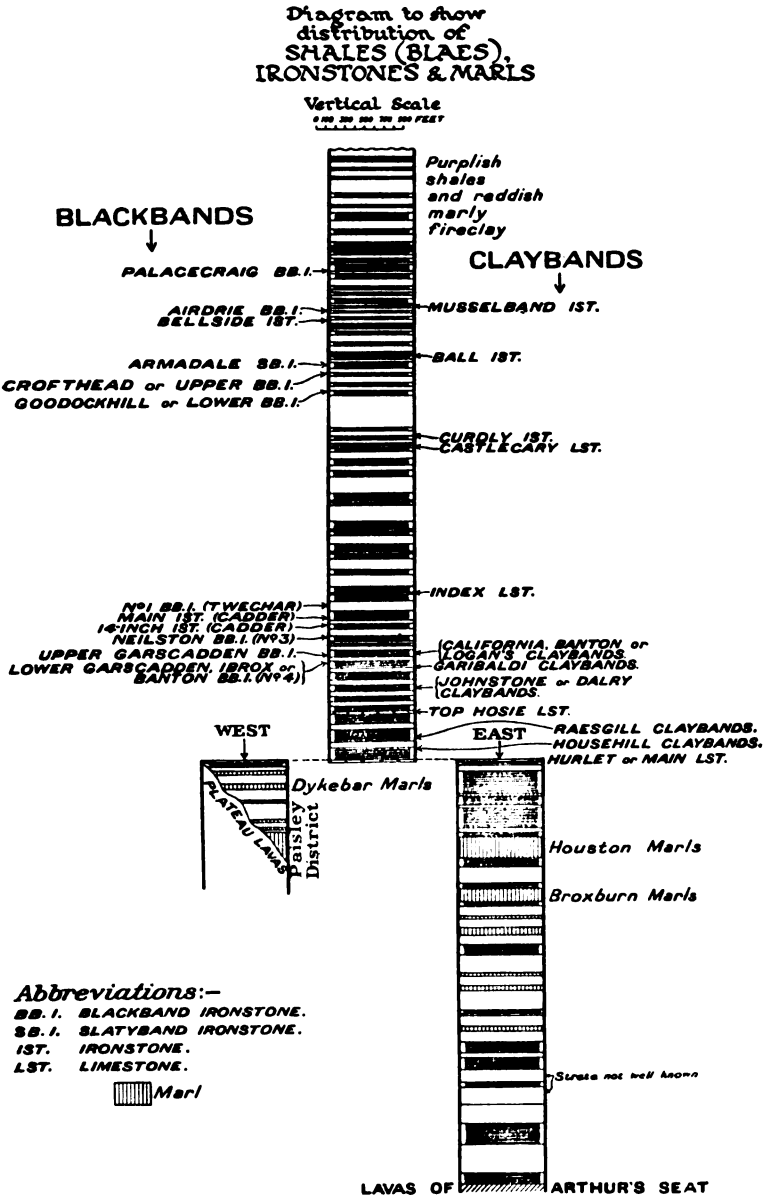


FIG. 6.

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place of the cold blast hitherto used in furnaces that blackband ores began to be utilised, but from this date onwards extensive search was made for them. It would be impossible to list all the horizons that have at one time or another contributed supplies of ore. Many were worked for a few years only and abandoned because of the thinning out of the seam and many furnaces were established throughout the Midland Valley that have long since disappeared. The period from 1860 onwards saw a complete revolution again in the condition of the iron industry; the importation of foreign ore began in the early sixties and by 1906 had reached to over two million tons; concurrently with this the output from Scottish sources decreased from two and a half million tons in 1876 (the maximum yield was 2,659,317 tons in 1880) to half a million tons (591,561 tons) in 1913. Among the factors contributing to this change were the introduction of steel for wrought iron as a material of construction and the consequent demand for imported high-grade non-phosphoric ores, the exhaustion of the richer and more accessible ironstone fields in Scotland, and the increasing cost of working its thinner and lower-grade seams.

The more important ironstone horizons are indicated in Fig. 6 (for the Central Coalfield) and in Plates I to III. The claybands that have been worked occur chiefly in the lower part of the Limestone Coal Group (Dalry or Johnstone Clayband, Garibaldi Claybands, California or Banton Claybands), and in the Lower Limestone Group (Househill Claybands of the East Paisley district, below the Blackhall Limestone; Raesgill Ironstones of Carluke above the Blackhall Limestone; etc.) but occur also in the Millstone Grit (Curdly Ironstone of Levenseat, near Fauldhouse, overlying the Roman Cement Limestone; Vicar's Bridge Ironstone at Dollar; etc.). In the Productive Coal Measures the ribs and layers of balls overlying worked coals have yielded, and still yield, considerable supplies of ore; such layers are commonly associated with the Armadale Ball and Shotts Furnace (Upper Drumgray) coals and are worked, when present, in conjunction with these seams; some of the balls are locally of a large size, but as a rule the layer is only a few inches thick. One or two sections of seams that have been worked in the Central Coalfield may be quoted as examples:—

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(1) Househill Claybands (Upper Seam), Nitshill.
(2) Johnstone Clayband, Nitshill.
(3) Garibaldi Claybands, Knightswood.
(4) California Claybands, Garscube.

| 1. | Ft. | in. | 2. | Ft. | in. |
|---|---|---|---|---|---|
| Clayband .. .. | 0 | 10 | Blaes .. .. | — | — |
| Blaes .. .. | 1 | 11 | Clayband .. .. | 0 | 8 |
| Clayband .. .. | 0 | 9 | Blaes .. .. | 3 | 4 |
| Blaes .. .. .. | 6 | 4 | Clayband .. .. | 1 | 0 |
| Clayband .. .. | 0 | 10 | | | |

| 3. | Ft. | in. | 4. | Ft. | in. |
|---|---|---|---|---|---|
| Blaes .. .. .. | — | — | Blaes .. .. | — | — |
| Clayband .. .. | 0 | 6 | Clayband .. .. | 0 | 6 |
| Blaes .. .. .. | 3 | 0 | Blaes .. .. | 3 | 0 |
| Clayband .. .. | 0 | 8 | Clayband 6 in. to | 1 | 2 |

All these are from localities near Glasgow.

The blackband ores are found mainly on the upper part of the Limestone Coal Group and in the Productive Coal Measures. To the former belong the Garscadden Blackbands of the Glasgow district, and the blackbands of the Possil, Cadder, Kilsyth, Bo'ness, and Denny fields; to the latter belong the blackbands of Crofthead (near Fauldhouse), Armadale, Airdrie and Palacecraig. The Crofthead Blackband is taken as the base of the Coal Measures in the Fauldhouse district (*see* p. 457) and is known also as the Upper Slatyband[1] in contradistinction to the Lower or Goodock-hill Slatyband which occurs in the upper part of the Millstone Grit. In the Limestone Coal Group of Midlothian[2] are the three Loanhead Ironstones and in the same group in Fife the Kelty, Comrie, Lochgelly and Inzievar Blackbands. To the Productive Coal Measures of Ayrshire belong the Dalmellington or Lugar Blackband at the base of the group and the Craigmark Blackband at the top.[3] The blackbands are all impersistent lenticular deposits, rarely exceeding 12 or 14 inches, although in pockets much greater thicknesses (up to 7 ft.) have been encountered. They are very often associated in compound seams with free or gas

[1] *See* footnote 1, p. 457.

[2] The Gilmerton Ironstone is in the Lower Limestone Group, between the Gilmerton and North Greens Limestones.

[3] For the stratigraphical positions of all these seams *see* Plates I to III.

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coal, a common sequence showing gas coal 3 in., on blackband 9 in., on gas coal 4 in., on free coal 12 in.; the ironstone dies away laterally but may reappear some little distance away. These ores appear to characterise certain groups of strata within which they come and go irregularly, while they also tend to recur in certain localities at two or three horizons not far apart although in adjoining districts they may be completely absent.

'*Marls*.' The deposits referred to under this term are practically confined to the Oil-Shale Group or to the sedimentary rocks that succeed the lavas in the West of Scotland. The Houston Marls[1] of West Lothian (locally as much as 200 ft. thick) lie between the Two Foot and Houston Coals in the upper part of the Oil-Shale Group, the Broxburn Marls at a somewhat lower horizon, between the Fells and Broxburn Shales. The Dykebar Marls of the Paisley district (up to 150 ft. in thickness) occur between the Hollybush and Dykebar Limestones. These marls consist of fine-grained argillaceous sediments in massive posts separated by ribs of hard sandstone or cementstone; they crumble readily on exposure and contain a variable proportion of carbonates in the form of scattered particles or of aggregates of small grains. It is difficult to explain the formation of thick beds of this character but they appear to represent the finer wind-borne detritus of volcanic rocks subjected to prolonged weathering under arid conditions.

(3) Distributions of Limestones and Shell Beds. (Fig. 7).

The marine limestones are the most important horizons for purposes of detailed stratigraphy. Although they play as a rule quite a subordinate role in the lithological sequence as compared with the sandstones and shales they are generally very persistent and readily recognisable. If we include with them the various bands of shales containing a marine fauna, the number of horizons at which organisms indicating definitely marine conditions[2] have been found is remarkable. The following list shows the number recorded up to the present; it should be read, however, in conjunction with the notes that follow:

[1] *See* Sir J. J. H. Teall, 'Petrological Notes on the Houston Marls; with Chemical Analyses by E. G. Radley,' *Trans., Edinb. Geol. Soc.*, vol. xi, part iii, pp. 327-337.

[2] The horizons at which specimens of *Lingula* alone have been obtained are not included.

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| | |
|---|---|
| Productive Coal Measures | Skipsey's Marine Band at top; also marine fossils at or near base. |
| Millstone Grit | up to 6 known. |
| Upper Limestone Group | 9 known. |
| Limestone Coal Group | at least 4 known. |
| Lower Limestone Group | 7 or 8 known. |
| Calciferous Sandstone Series (Oil-Shale Group)[1] | 9 or 10 known. |

It must be added that the marine horizons listed are very unequal as regards faunal content or stratigraphical value. Some of them are beds of shale (blaes) in which a few marine fossils have been locally obtained. Those in the Upper and Lower Limestone Groups again consist, as a rule, of definite and persistent limestones overlain by a variable but often thick series of calcareous and fossiliferous shales.

Before dealing with the various shell-beds found in the Scottish Carboniferous it may be useful to classify the fossils in their relative order of value for stratigraphical purposes.

(1) Fossils indicating marine conditions.

(2) The non-marine lamellibranchs or "mussels."

(3) Fishes, plants, *Lingula*, Entomostraca, etc.

All fossil evidence is valuable and should be carefully recorded; plant, fish and "mussel" beds may be of much use locally as guides to position, but in the present state of our knowledge by far the most reliable "index" fossils are provided by the members of group (1).

In the Calciferous Sandstone Series of East Fife (Pittenweem to Anstruther coast-section) at least ten truly marine zones are known,[2] while in the Oil-Shale Group of the Lothians marine fossils have been obtained at the following horizons:—

(1) From a limestone low down in the Granton Sandstone.

(2) Near the base of the Wardie Shales.

(3) Pumpherston Shell Bed, below the Pumpherston Shales.

[1] The Cementstones of Liddisdale contain a thoroughly marine fauna (Thorlieshope and Larriston Burn Limestones), while in the Cove Harbour section, near Cockburnspath, a thin band of calcareous shales yielding *Sanguinolites* has been referred to a horizon near the base of the Cementstone Group.

[2] *See* J. W. Kirkby *in* "Geology of Eastern Fife," *Mem. Geol. Surv.*, 1902, pp. 77-95, and 103.

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(4) From a 17-inch band overlying the Camps Shale at Rosyth.
(5) Dunnet Shell Bed above the Under Dunnet Shale (at Livingston, Pumpherston and Straiton).
(6) Raeburn Shell Bed under the Raeburn Shale.
(7) Fraser Shell Bed under the Fraser Shale.
(8) and (9) At two horizons between the Fraser Shale and the Hurlet Limestone.

The most persistent marine bands known in the Oil-Shale Group are those numbered (3) and (6). Beds (6) to (9) can be recognised outside the Lothians area in the Strathaven district (Sheet 23) in the sediments present there above the Calciferous Sandstone lavas.[1]

| *Lothians.* | *Strathaven.* |
|---|---|
| Marine Band (No. 9). | Under Limestone. |
| Marine Band (No. 10). | Basket Shell Bed. |
| Fraser Shell Bed. | Netherfield Limestone. |
| Raeburn Shell Bed. | Marine band. |

In the Glasgow-North Ayrshire province again there are at least four marine horizons present in the post-lava sediments—the Dykebar, Hollybush, Blackbyre (Broadstone of Ayrshire) and Baldernock Limestones. The Upper Calciferous Sandstone sediments of the Dunbar-Cockburnspath area include the Cove Lower and Upper Limestones which may be identified with the Dun and Woodend Limestones of Northumberland;[2] while thin encrinital limestones (including the Sandersdean Limestone) are known in the area south and south-east of Haddington, in strata which may be correlated with part of the Upper Oil-Shale Group. It must be remembered when dealing with these marine bands, that the Calciferous Sandstone of Scotland was laid down in more or less separate areas and under varying conditions of deposition (*cf.* p. 489). The Hurlet Limestone and the overlying strata are widespread and persistent deposits;[3] but the beds underlying the

[1] Representatives of the Raeburn and Fraser Shales are also found at Strathaven (*see* p. 532). A very rapid overlap of the Calciferous Sandstone sediments on the lavas takes place here and their maximum known thickness is between 350 and 400 feet. The evidence for a possible connection between the Lothians area and that of Strathaven in late Oil-Shale times is discussed by C. H. Dinham in 'Economic Geology Central Coalfield, Area IX,' *Mem. Geol. Surv.*, 1921, pp. 8-10.

[2] C. T. Clough *in* 'Geology of East Lothian,' *Mem. Geol. Surv.*, 1910, p. 46; *see also* W. Gunn, *Geol. Mag.*, 1898, p. 347.

[3] It is mainly for this reason that the Hurlet Limestone was selected as the base of the Carboniferous Limestone Series in Scotland.

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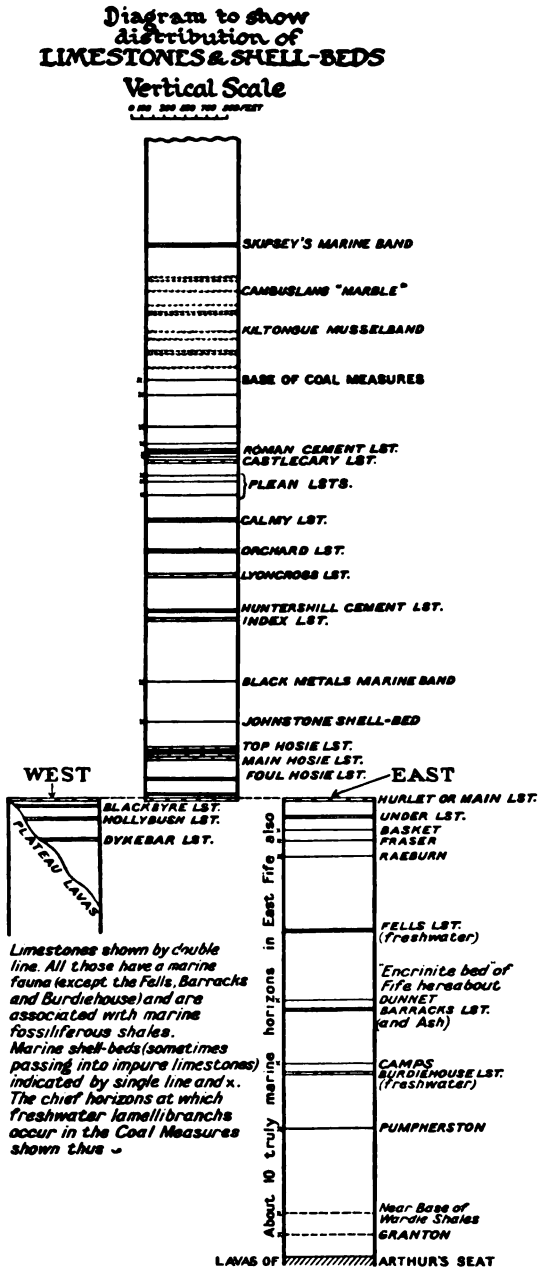


FIG. 7.

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Hurlet exhibit on the other hand marked lithological variations. The marls and thick coals of the Paisley district, the sandstones and conglomerates of the Campsie and Kilpatrick districts,[1] the lagoonal deposits of the Lothians Oil-Shale Group, and the more varied sediments of East Fife with their thin marine limestone and coals, were all more or less contemporaneously laid down in areas separated by land-barriers of older rocks (Calciferous Sandstone lavas, Old Red Sandstone, etc.). The difficulties of correlating these beds even within one district is well exemplified in the account of the Upper Calciferous Sandstone sediments given by Mr. C. H. Dinham in the 'Geology of the Glasgow District' (1925, pp. 14-31). Much work requires to be done on the faunas of the various marine bands in the Calciferous Sandstone of East Fife and the Lothians before correlations can be established and before comparisons can be made with the life zones proved in the North of England succession.

The Lower Limestone Group contains a number of limestones overlain by calcareous and often richly fossiliferous shales. The limestones include the Hurlet (or Main) at the base, the Blackhall near the middle and the Hosie seams (three or four in number) at the top of the group. The Blackhall Limestone (or Foul Hosie) is probably represented in the Bathgate district (Sheet 31) by the Petershill Limestone and is identified with the Charlestown Main of West Fife and with the Seafield Tower Limestone of the Kinghorn coast.[2] The Top Hosie again may be correlated with the Upper Carriden of Bo'ness, and with the Upper Kinniny of West Fife. A detailed comparison of the West of Scotland Lower Limestones with those of Midlothian and of East Lothian has not yet been fully established, but in the Table given below (p. 519) a number of tentative correlations have been advanced. The late Prof. P. Macnair devoted much research to this problem and the reader should consult the paper contributed by him to the *Proceedings* of the Royal Society of Edinburgh.[3] Macnair obtained from the shale between the Hurlet Limestone and the Hurlet Coal (the Alum Shale of Campsie) a fauna which he claimed to be characteristic of this horizon over a wide area. The members of this 'Hurlet' or Abden Fauna," as listed by Macnair,[4] are:—

[1] A little to the north of Glasgow.

[2] Sometimes known as the Chapel Limestone.

[3] 'The Hurlet Sequence in the East of Scotland and the Abden Fauna as an Index to the position of the Hurlet Limestone, *Proc. Roy. Soc. Edin.*, 1917, vol. xxxvii, pp. 173-209.

[4] *Ibid.*, p. 204.

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Sanguinolites abdenensis *R. Eth., jun.*
Sanguinolites costellatus *M'Coy.*
Streblopteria ornata (*R. Eth. jun.*)
Posidonomya corrugata *R. Eth., jun.*
Actinopteria persulcata (*M'Coy*)
Schizophoria resupinata (*Martin*)
Productus longispinus *J. Sow.*
Productus semireticulatus *Martin*
Lingula squamiformis *Phill.*
Orbiculoidea nitida (*Phill.*)
Archaeocidaris urei (*Flem.*)
Euphemus urei (*Flem.*)
Serpulites carbonarius *M'Coy*
Orthoceras sp.
Goniatites.

The most characteristic member of his assemblage and the only one that can be regarded as at all diagnostic is the fossil *Sanguinolites abdenensis.* None of the members, however, are restricted to this particular horizon and some indeed have a wide vertical range. Thus, although the fauna as a whole points to a definite stratigraphical position at the base of the Lower Limestone Group, it must be used with caution and in conjunction with other criteria (e.g. general stratigraphical considerations).

The following table shows the limestones present in the Lower Limestone Group of North Ayrshire, Central Coalfield, West Fife and Midlothian:—

| *North Ayrshire* | *Central Coalfield* | *West Fife* | *Midlothian* |
|---|---|---|---|
| Limestone D | Top Hosie (1) | Upper Kinniny (8) | *Bellerophon* Limestone (13) |
| Limestone C | Second Hosie (2) | Mid Kinniny (9) | Bilston Burn |
| Limestone B | Mid Hosie (3) | Lower Kinniny (10) | Upper Vexhim |
| | Main Hosie (4) | Duloch Marine Band (11) | Lower Vexhim |
| Limestone A | Blackhall (5) | Charlestown Main (12) | North Greens (14) |
| — | Craigenhill (6) | Charlestown Green | " Five-Foot " (15) |
| Dockra | Main or Hurlet (7) | Charlestown Station | Gilmerton (16) |
| | | | (Bone-Bed Limestone) |

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Notes:—

(1) Calderwood Cement of East Kilbride; *Lingula* Limestone of Carluke.

(2) Anvil Limestone of East Kilbride; 1st Kingshaw of Carluke

(3) Middle Limestone of East Kilbride; 2nd Kingshaw of Carluke.

(4) Under Limestone of East Kilbride; Birkfield of Carluke. The Middle and Under seams coalesce to form the Hairmyres Limestone of the west side of the East Kilbride field; in North Ayrshire similarly Limestone B is regarded as the equivalent of both Mid and Main Hosie.[1]

(5) Wee Limestone of East Kilbride; Foul Hosie of Carluke; Fankerton Limestone of Denny;[2] Petershill of Bathgate.

(6) Sandy encrinital limestone (Shields Bed) of Campsie;[3] Limestone C of Bannock Burn.[4]

(7) Main Limestone of Carluke, Cobbinshaw, etc.; Limestone D of Bannock Burn; Murrayshall of Stirling; ? West Kirkton of Bathgate.

(8) Upper (No. 1) Carriden Limestone of Bo'ness.

(9) Mid (No. 2) Carriden Limestone of Bo'ness.

(10) Lower (No. 3) Carriden Limestone of Bo'ness; Wairdlaw Limestone of Bathgate Hills.

(11) Also found at Bo'ness.

(12) No. 5 Limestone of Bo'ness; Seafield Tower of Kinghorn; Chapel Limestone; limestone of Duloch, Lathalmond and Roscobie quarries.

(13) Harelaw Limestone of Carlops.

(14) No. 2 Limestone of south-east side of Midlothian basin (Tyne Water, etc.).

(15) Occurs between Gilmerton and North Greens Limestones at Loanhead.

(16) No. 1 Limestone of south-east side of Midlothian basin (Tyne Water).

In the above table the Fife and Midlothian sequences are put in separate columns since many of the correlations given in order

[1] 'Geology of North Ayrshire,' *Mem. Geol. Surv.*, 1930, p. 135.

[2] C. H. Dinham *in* 'Summary of Progress for 1919,' *Mem. Geol. Surv.*, 1920, p. 38.

[3] 'Geology of Glasgow District,' *Mem. Geol. Surv.*, 1925, p. 41.

[4] Four or five miles south of Stirling; C. H. Dinham, *loc. cit.*

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to try and link them with each other and with the West of Scotland must be regarded meanwhile as more or less tentative. In recent Survey publications,[1] for example, the Top Hosie Limestone is correlated with the Mid Kinniny and the Upper Kinniny is taken as the equivalent of the Johnstone Shell Bed of the Central Coalfield (p. 524). The correlation given in the table, however, seems to be more in consonance with the evidence available. Reasons will be given later (pp. 524-6) for regarding the marine band above the Sulphur Coal of West Fife (Smithy Coal of Bo'ness) as the equivalent of the Johnstone Shell Bed. General stratigraphical considerations again indicate that the Upper Kinniny Limestone (Upper Carriden) should be correlated with the Top Hosie. It is true that *Posidonomya corrugata* has been found in association with both the Mid Kinniny and Mid Carriden Limestones, but this shell cannot be said to have the very narrow range once ascribed to it and its occurrence at this horizon does not by itself prove stratigraphical equivalence with the Top Hosie. The three Kinniny Limestones clearly correspond with the three highest Carriden Limestones. In the case of the Midlothian sequence I have followed Clough[2] in taking the 20-inch limestone found in the Bilston Burn 40 feet or so above the Bilston Burn Limestone, as the top of the Lower Limestone Group; this band can be followed round much of the Midlothian basin as a thin irony limestone overlain by *Lingula*-bearing shales (e.g. Harelaw Limestone of Carlops) while a similar band noted in a boring at Ormiston in East Lothian, 114 feet below No. 2 Diamond Coal (14 feet below the Hauchielin), is probably on the same horizon. The Bilston Burn and Vexhim Limestones may be correlated with the lower Hosie Limestones, and the North Greens with the Blackhall and with the Charlestown Main. As regards the lowest limestone of the Group I follow Maufe in correlating the Hurlet Limestone with the Charlestown Station[3] and suggest that its equivalent in the Midlothian succession is the Gilmerton. These tentative correlations of the Lower Limestones of Fife and Midlothian are based upon the general sequences established within these areas. The Gilmerton Limestone was adopted as the base of the Lower

[1] *See* 'Summary of Progress for 1923,' *Mem. Geol. Surv.*, 1924, p. 119.

[2] 'Geology of the Neighbourhood of Edinburgh,' *Mem. Geol. Surv.*, 1910, p. 184.

[3] *Ibid.*, pp. 52, 161.



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Limestone Group in the Edinburgh District Memoir but the following qualification was added:

" A considerable amount of stratigraphical and palaeontological evidence has been accumulated, partly by Mr. Macconochie, which makes it not improbable that a lower limestone, the base of which in the Burdiehouse Burn lies 130 ft. below the Gilmerton Limestone really corresponds to the Lower Longcraig Limestone of Dunbar, which, in that locality, is taken as the base of the Carboniferous Limestone Series. The little limestone[1] referred to rests on a calcareous shale with abundant remains of *Rhipidomella* (*Orthis*) underlain by a thin pyritous shale, a few inches thick, with fish remains and *Lingula*. A shale with *Schizophoria* and *Rhipidomella* and a similar fish-bed occur below the Lower Abden Limestone on the coast of Fife, which in all probability corresponds in position with the Lower Longcraig of Dunbar, although neither the shale nor the fish bed has there been found in connection with it."

C. B. Crampton[2] correlated the Lower Longcraig of Dunbar with the Nodular Dolomitic Limestone of Aberlady and with Kirkby's Pseudo-brecciated Limestone of St. Monans in East Fife.[3] Macnair,[4] relying mainly on the occurrence of certain members of his Abden Fauna (p. 519) in the shales underlying the limestones, placed the following on the same stratigraphical horizon.

Hurlet Limestone
Charlestown Station Limestone
1st (Lower) Abden Limestone
Bone-bed Limestone of Midlothian
Upper Longcraig Limestone of Dunbar.
Pseudo-brecciated Limestone of St. Monans[5]

After a careful consideration of the available evidence I venture to suggest the following correlations as most in accord with what we know of the succession in the Lower Limestone Group within the different areas. I put them forward however, merely as a possible basis for further research:—

[1] Now known as the Bone-bed Limestone.

[2] 'Limestones of Aberlady, Dunbar and St. Monans,' *Trans. Edinb. Geol. Soc.*, 1905, vol. viii, p. 374.

[3] 'Geology of East Fife,' *Mem. Geol. Surv.*, 1902, p. 150.

[4] *Proc. Roy. Soc. Edin.*, 1917, vol. xxxvii.

[5] For these and other correlations *see* Sheet of Vertical Sections attached to Macnair's paper.

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| | |
|---|---|
| Blackhall Limestone. | Charlestown Main.<br>North Greens.<br>No. 2 Tyne Water.<br>Middle Skateraw of Dunbar. |
| Craigenhill Limestone. | Charlestown Green.<br>Limestone between North Greens and Gilmerton.<br>? Lower Skateraw of Dunbar. |
| Hurlet Limestone (base of Lower Limestone Group). | Charlestown Station.<br>Gilmerton.<br>No. 1 Tyne Water.<br>? Upper Longcraig of Dunbar. |
| Near top of Calciferous Sandstone Series. | Limestone below Charlestown Station.<br>?Bone-bed Limestone of Midlothian (= 1st Abden)<br>Lower Longcraig of Dunbar. |

The Middle Skateraw has been definitely correlated with the Acre of Northumberland (*see* p. 474).

The present Survey practice, however, is to regard the Bone-bed Limestone as the base of the Midlothian Lower Limestone Group and I have followed this custom in Plate IV. It must be admitted that to take the Gilmerton as the base of the Lower Limestone Group raises two immediate difficulties.

(1) The Hurlet, or Abden, Fauna, has been recorded by Macnair from the shales below the Bone-bed Limestone and also below the 1st Abden of Fife; not from below the Gilmerton.

(2) A thin " bone-bed " made up of fish-remains is found at the base of the shale underlying the Hurlet Limestone at Campsie.

Nevertheless the adoption of a Hurlet—Charlestown Station—Bone-bed Limestone stratigraphical horizon appears to present at least equally formidable difficulties.

The Hawthorn Limestone of Muirkirk and Coalburn, the Patna of Dalmellington, and the Captain's Bridge Limestone of Dailly are all regarded as on the same stratigraphical horizon as the Hurlet. At Muirkirk and Coalburn the Hosie Limestones are known as the McDonald Limestones.

For the fossils characteristic of the Lower Limestone Group *see* Fig. 2 and p. 470. It may be also noted that on the top of the

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Blackhall or Foul Hosie Limestone in the West of Scotland there is a band of richly fossiliferous blaes known as the *Neilson Shell Bed*, which has been used locally as a index horizon.[1] The bed is remarkable, however, for the abundance of species and for their unusually excellent state of preservation rather than for the occurrence of special forms.

*Limestone Coal Group*:—The horizons at which marine fossils have been obtained within this group may be listed as follows:—

(1) The Black Metals[2] Marine Band.

(2) Maich Shell Bed of North Ayrshire, occurring a few fathoms below the Dalry Blackband Ironstone; also at or near the same horizon in the Glasgow district, and at Bo'ness (*see below*).

(3) From shales between the Smithy and Easter Main Coals at Bo'ness.

(4) The Johnstone Shell Bed; marine band above Smithy Coal at Bo'ness and above Sulphur or Stink Coal of West Fife.

The Johnstone Shell Bed and the Black Metals Marine Band are both very valuable index horizons. The former is frequently developed as a thin shelly limestone or 'lumachelle' overlain by fossiliferous shales. It is important as the first marine horizon to be encountered below the workable coals of the Limestone Coal Group. It has been recorded throughout the Central Coalfield from Glasgow and Paisley eastwards to Carluke, Wilsontown and Bathgate; it is present also in the Douglas, Coalburn and Muirkirk districts; and it occurs throughout North Ayrshire. The following list gives the fossils that have been obtained from the Johnstone Shell Bed in the Glasgow District:—

List of fossils obtained from the Johnstone Shell Bed in the Glasgow district.

| | Localities | | Localities |
|---|---|---|---|
| Zaphrentis *cf.* enniskilleni *M. Edw.* | 1 | Productus *cf.* concinnus *J. Sow.* | 2, 3 |
| Crinoid ossicles .. .. .. | 1, 2 | ,, lobatus *J. Sow* .. | 1 |
| Serpula sp. .. .. .. | 1 | ,, muricatus *J. Sow* .. | 1 |
| Camarotoechia pleurodon (*Phill.*) | 2 | Schizophoria resupinata (*Mart.*) | 1 |
| Composita ambigua (*J. Sow.*) .. | 1 | Aviculopecten sp. .. .. | 2 |
| Lingula mytiloides *J. Sow.* .. | 4 | Ctenodonta undulata (*Phill.*) .. | 4 |
| ,, squamiformis *Phill.* | 1, 2, 3 | Edmondia laminata (*Phill.*) ? *var.* sub-laevis *Hind* .. .. | 2 |
| Orbiculoidea nitida (*Phill.*) .. | 1, 4 | Edmondia unioniformis (*Phill.*) | 1 |
| Productus concinnus *J. Sow.* .. | 1 | | |

[1] *See*, for example, J. Neilson in *Trans. Geol. Soc. Glasgow*, vol. xiv, part iii. 1913, pp. 61, 68, 69.

[2] *See* p. 509.

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| | Localities |
|---|---|
| Grammatodon sp. .. .. | 1 |
| Lithodomus lingualis (*Phill.*) .. | 1 |
| Myalina flemingi (*M'Coy*) .. | 4 |
| ,, verneuilli (*M'Coy*) .. | 1 |
| Nucula luciniformis ? *Phill.* .. | 4 |
| Nuculana attenuata (*Flem.*) .. | 2, 4 |
| Protoschizodus axiniformis (*Portl.*) | 1, 2 |
| ,, ? .. | 4 |
| Sanguinolites costellatus (*M'Coy*) | 1 |
| Sanguinolites variabilis (*M'Coy*) | 4 |
| ,, sp. .. .. | 2 |
| ? Sedgwickia gigantea (*M'Coy*) | 1 |
| Streblopteria ornata (*R. Eth., jun.*) | 2, 4 |
| Bucanopsis sp. .. .. .. | 2 |
| Euphemus urei (*Flem.*) .. | 4 |
| Orthoceras attenuatum *Flem.* | 2 |
| ,, cylindraceum *Flem* | 4 |

Localities: (1) New Ironstone Pit (1905) Pollok, Corkerhill. (2) No. 1 Bore Cardowan. (3) No. 1 Bore Cardyke. (4) Borings near Auchengeich, Chryston.

The shell-bed usually occurs in two leaves (sometimes separated by several fathoms of strata) and the upper one is often characterised by its abundance of *Lingula squamiformis* and *Lingula mytiloides* associated with *Naiadites magna*. I have correlated the Johnstone Shell Bed with the marine band found above the Smithy Coal of Bo'ness and its equivalent in West Fife, the Sulphur or Stink Coal. The following lists show the fauna from this horizon:—

(1) From above Smithy Coal at the Chance Pit, Bo'ness.[1]

(2) From above Stink Coal in boring near Carnock Estate, West Fife.

(3) From above Stink Coal, Mary Pit, Lochgelly, Fife.

(1)

Archaeocidaris ?
Lingula mytiloides *J. Sow.*
,, squamiformis *Phill.*
Orbiculoidea nitida (*Phill.*)
Productus sp.
Aviculopecten inæqualis *Hind.*
Ctenodonta laevirostris (*Portl.*)
Edmondia sulcata *Phill.*
Myalina verneuili *M'Coy*
Nucula luciniformis *Phill.*
Protoschizodus spp.
Prothyris sp. nov.
Schizodus sp.
Sanguinolites costellatus (*M'Coy*)
Streblopteria ornata (*R. Eth. jun.*)
Bucanopsis
Euphemus urei (*Flem.*)
Orthoceras attenuatum *Flem.*

(2)

Lingula mytiloides (*J. Sow.*)
,, squamiformis (*Phill.*)
Productus *cf.* longispinus. *J. Sow.*
Camarotoechia sp.
Ctenodonta laevirostris (*Portl.*)
Edmondia ?
Myalina verneuilli (*M'Coy.*)
Protoschizodus axiniformis (*Portl.*)
Sanguinolites costellatus (*M'Coy*)
,, sp.
Streblopteria ornata (*R. Eth. jun.*)
Ptychomphalina *cf.* atomaria (*Phill.*)
Euphemus urei (*Flem.*)
Bellerophon ?

[1] Partly from material collected by the Geological Survey, partly from lists given by Mr. H. M. Cadell in 'The Rocks of West Lothian,' 1925, pp. 212-213.

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(3)

Crinoid ossicles
Lingula mytiloides *J. Sow.*
,, squamiformis *Phill.*
Productus productus (*Mart.*)
Edmondia ?
Myalina *cf.* flemingi (*M'Coy*)
*Cf.* Sanguinolites variabilis *M'Coy.*
Sanguinolites sp. (*finely ornamented, same as form in Glasgow district*)
Streblopteria ornata (*R. Eth. Jun.*)
Euphemus *cf.* urei (*Flem.*)
Orthoceras sp.

Both at Bo'ness and in Fife the shell-bed occurs in two leaves. The marine fossils recently obtained by Mr. H. M. Cadell from shales between the Smithy and Easter Main coals of Bo'ness may be regarded as an upper leaf of the Smithy Coal band.[1]

A recent boring at Ormiston in East Lothian (Sheet 33) cut a marine horizon (again in two leaves) between the Hauchielin (Arniston Parrot) and No. 2 Diamond coals (*see* Plate II). The species obtained here are as follows:—

Productus *cf.* productus (*Mart.*)
,, sp.
Edmondia ?
Myalina ?
Nucula luciniformis (*Phill.*)
Pinna sp.
Streblopteria ornata (*R. Eth., jun.*) *abundant.*
Trilobite fragment

There can be no doubt that this marine horizon represents the Bo'ness Smithy Coal band. It has not so far been recorded from the Midlothian basin.[2]

In North Ayrshire marine fossils have been obtained locally from a horizon a little below the Dalry Blackband (near the Garibaldi Clayband position); this band, the Maich Shell Bed, has yielded *Lingula squamiformis, Aviculopecten inequalis, A. dissimilis, Edmondia,* ? and a thick shelled *Myalina.* It is represented also in the country north-east of Glasgow by a bed yielding mainly *Lingula.* In the Bo'ness field Mr. H. M. Cadell has noted the occurrence of *Edmondia* about 20 feet above the Lower Ironstone; this ironstone can be correlated with the Pittencrieff Ironstone of Fife and must lie at or near the position of the Garibaldi Clayband. (*See* Plate I). The marine band occurring in the lower part of the thick group of shales known as the Black Metals (p. 509) is persistent throughout the Central Coalfield[3] and has

[1] Specimens were presented to the Survey by Mr. Cadell, and identified by Mr. Pringle. They are all forms that occur in the lower marine band.

[2] *Lingula squamiformis* occurs a few feet above the North Coal at Niddrie.

[3] M. Macgregor in 'Summary of Progress for 1923,' *Mem. Geol. Surv.*, 1924, pp. 110-112.

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been recognised in West Fife;[1] in North Ayrshire, Douglas and Muirkirk, however, only *Lingula* has so far been recorded from this horizon.

*Upper Limestone Group.* In the Upper Limestone Group the principal limestones are the Index, Lyoncross, Orchard, Calmy and Castlecary. The Index is poorly developed in parts of Fife[2] and locally in the West of Scotland is cut out by a slight unconformity[3] at the base of the overlying Bishopbriggs Sandstone (p. 507). The Lyoncross is not so persistent as the other seams; it has not been recognised anywhere along the eastern margin of the Central Coalfield, nor does it appear to be present in Midlothian or East Lothian; in Fife a thin shelly blaes is sometimes found at this horizon. The absence of the Castlecary over parts of the Central Coalfield, North Ayrshire and Fife has been already referred to (p. 462). In addition to these limestones, however, marine fossils have been obtained in thin limestones or calcareous shales at several other horizons, as follows:—

(1) From a thin limestone lying a few fathoms above the Index and known as the Huntershill Cement from its occurrence in the old sandstone quarries of that name north of Bishopbriggs, near Glasgow.

(2) From three horizons[4] (thin limestones or limy shales) between the Calmy and Castlecary seams. These marine bands are best developed in the Plean district and may therefore be spoken of as the *Plean Limestones*; the lowest of the three (*Plean* No. 1) is the most widespread.

The following table shows the names of the principal limestones in different areas:—

[1] It has not been recorded yet in Central Fife; for its possible equivalent in Midlothian, *see* p. 557.

[2] Usually a thin band of shelly shales: locally a thin limestone may be present and this reaches a maximum of 1½ ft. north-east of Dunfermline.

[3] 'Geology of Glasgow District,' 1925, p. 69; 'Geology of North Ayrshire,' 1930, p. 185.

[4] Very locally there may be as many as five.

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| Douglas. | North Ayrshire. | Central Coalfield. | Fife. | Midlothian. |
|---|---|---|---|---|
| Castlecary. | Castlecary | Castlecary or Levenseat | Castlecary | No. 6. |
| Gill (1) | Upper Linn or Linn Spout | Calmy (3) | Calmy or Jenny Pate | No. 5 |
| Ponfeigh | Lower Linn or Linn Brig | Orchard (4) | Orchard | Extra |
| Ellenora | Third Post | Lyoncross (5) | (Thin shelly blaes) | Not known |
| Index (2) | Highfield or Index | Index (6) | Index | No. 4. |

Notes:—

(1) Blue Tour of Muirkirk.
(2) Seven Foot of Muirkirk.
(3) Also known in different localities as the Arden, Robroyston, Garnkirk, Hirst, Shirva, Gair, or Dykeneuk.
(4) Gillfoot of Carluke. Frequently in two leaves.
(5) Holeburn of Giffnock.
(6) Cowglen of Giffnock, etc.

For the fossils characteristic of the Upper Limestone Group *see* Fig. 2 and p. 470.

*Millstone Grit*:—Marine beds occur also in the Millstone Grit, the most characteristic being the thin limestone near the base known as The Cementstone Limestone or Roman Cement.[1] It is a widespread horizon within the Central Coalfield, persisting often in areas where the Castlecary is absent and in such cases serving as a useful index-bed. It has also been recognised in Midlothian.[2] In the North Stirlingshire part of the Central Coalfield (Plean, etc.) where the Millstone Grit attains its maximum thickness (over 1100 ft.) no less than six marine horizons are known. As a rule, however, the upper part of the Millstone Grit does not contain evidence of marine conditions.

*Coal Measures*:—Marine Shells have been recorded as occurring locally at or near the base of the Productive Coal Measures of the

[1] *See* pp. 487.

[2] In the Bilston Burn and in the South Esk; *see* 'Geology of the Neighbourhood of Edinburgh,' *Mem. Geol. Surv.*, 1910, pp. 247, 251.

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Central Coalfield,[1] but between this and Skipsey's Marine Band at the top of the Group the fauna is, as far as is known, entirely estuarine or freshwater.[2]

The occurrence of freshwater limestones at certain horizons may be noted here. The best known of these is the Burdiehouse Limestone which forms the boundary between the Upper and Lower Oil-Shale Groups. This is a dark grey to cream-coloured, usually banded rock, contained cherty layers and abundant plant, fish, and entomostracan remains. It varies in thickness from about 5 up to nearly 50 feet and has been extensively quarried locally (Newpark, Harburnhead, Burntisland and Straiton—all localities in Sheet 32) for iron smelting, gas purification and other purposes. Other thinner and less persistent limestones of the same general type occur within the Oil-Shale Series of the Lothians (the Barracks Limestone at the base of the Dunnet Shales and the Fells Limestone underneath the shale of the same name. A number of thin limestones characterised by the freshwater shell *Naiadites obesa* occur in the Calciferous Sandstone of East Fife. The muddy sandstones of the Ballagan Beds[3] and the few thin impure limestones, occasionally with *Spirorbis*, found in the Barren Red Measures may also be referred to. The East Kirkton Limestone of the Bathgate Hills, assigned to a late stage in Calciferous Sandstone times, has been referred to the action of thermal springs filling in a shallow lagoon in a volcanic area.

As regards the proportions in which true limestones occur in the Upper and Lower Limestone groups the following figures may be given:—

[1] *See* W. Grossart, 'On the Upper Coal Measures of Lanarkshire,' *Trans. Geol. Soc. Glasgow*, vol. iii, part 1, 1868, p. 96; 'Explanation of Sheet 31,' *Mem. Geol. Surv.*, 1879, p. 74; J. Neilson in *Trans. Geol. Soc. Glasgow*, vol. xi, part i, 1898, pp. 147, 149.

[2] *Lingula* is rarely found. R. Dunlop recorded in the *Transactions* of this Society (vol. viii, 1888, p. 342 and vol. xiii, part 1, 1907, p. 35) marine fossils (*Pterinopecten papyraceus*, *Orthoceras* sp. and a species of Goniatite) from a horizon between the Kiltongue and Virtuewell Coals. The specimens were obtained from the North Calder Water at Calderbank, and there is no doubt came from a loose boulder of Skipsey's Marine Band.

[3] The Cementstone Group has yielded so far very few fossils. Plant remains, thin-shelled Entomostraca and fish-scales have been obtained in the Glasgow district. At the Heads of Ayr it has yielded *Estheria striata* (Münster), *Lingula mytiloides* J. Sow. *Anthracomya minima* Ludwig, and fish-remains. *Anthracomya minima* is also recorded from the same group at Dailly.

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| | | Total thickness of Group. | Thickness of Limestones. | Percentage of Limestone to Total Thickness. |
|---|---|---|---|---|
| A. | Upper Limestone Group. | | | |
| | (1) Fife. | | | |
| | Strathore .. .. .. .. | 738 | 12½ | 1.7 |
| | Culross .. .. .. .. | 1682 | 11¾ | 0.7 |
| | (2) Central Coalfield. | | | |
| | Plean .. .. .. .. | 1350 | 14¾ | 1.1 |
| | Kilsyth .. .. .. .. | 1320 | 19 | 1.4 |
| | Levenseat (near Fauldhouse) .. | 660 | 20 | 3.0 |
| | Quarter (Hamilton) .. .. | 408 | 20 | 4.9 |
| | (3) Midlothian. | | | |
| | Niddrie .. .. .. .. | 1068 | 20½ | 1.9 |
| | Dalkeith (Lady Victoria Pit) .. | 593 | 10 | 1.7 |
| | Loanhead .. .. .. .. | 776 | 32½ | 4.2 |
| | (4) Ayrshire. | | | |
| | Dalry .. .. .. .. | 327 | 73 | 22.3 |
| | Galston .. .. .. .. | 258 | 31 | 12.0 |
| | Muirkirk .. .. .. .. | 588 | 40 | 6.8 |
| | New Cumnock .. .. .. | 390 | 30 | 7.7 |
| | Dalmellington .. .. .. | 480 | 61 | 12.7 |
| B. | Lower Limestone Group. | | | |
| | (1) Fife. | | | |
| | St. Monans .. .. .. .. | 360 | 35 | 9.7 |
| | Dunfermline .. .. .. | 600 | 28 | 4.7 |
| | Charlestown .. .. .. .. | 516 | 48 | 9.3 |
| | (2) Central Coalfield. | | | |
| | Wilsontown .. .. .. .. | 468 | 39½ | 8.4 |
| | Carluke .. .. .. .. | 238 | 24 | 10.1 |
| | Stonehouse (S. of) .. .. .. | 150 | 17½ | 11.6 |
| | Paisley .. .. .. .. | 198 | 18 | 9.1 |
| | Thorntonhall .. .. .. | 108 | 30 | 27.7 |
| | (3) Midlothian. | | | |
| | Bilston Burn (Loanhead) .. .. | 690 | 140 | 20.3 |
| | Tyne Water .. .. .. | 220 | 118 | 53.6 |
| | (4) Ayrshire. | | | |
| | North Ayrshire .. .. .. | 120 | 54 | 45.0 |
| | Central Ayrshire (Inchgotrick) .. | 17 | 7 | 41.2 |
| | New Cumnock .. .. .. | 90 | 25 | 27.7 |
| | Muirkirk .. .. .. .. | 72 | 39 | 54.2 |

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The figures are, of course, merely approximate; only solid or fairly solid limestones have been taken into consideration. The table, however, brings out (1) the considerably greater proportion of limestone in the Lower Limestone Group, and (2) the *general* increase in calcareous content in both groups as they are followed in a south-westerly direction.

Figure 7 also indicates the chief horizons at which "mussels" have been obtained in the Productive Coal Measures of the Central Coalfield. They may be listed as follows:—

(1) A few fathoms below the Armadale Main Coal.
(2) Between the Mill and Shotts Gas Coals.
(3) Above the Shotts Gas Coal.
(4) Above the Shotts Ball or Furnace Coal (= Upper Drumgray)
(5) Kiltongue Musselband.
(6) Musselband Ironstone.
(7) Above Splint Coal.
(8) Cambuslang Marble, between the Pyotshaw and Ell Coals. Also at several horizons above the Ell Coal.

"Mussels" are also recorded at many horizons in the Coal Measures of Fife, Midlothian, Ayrshire, Douglas and other districts, but so far little is known regarding the distribution and range of the different species.[1] A careful study and comparison of the faunas of the various "musselbands" in the Scottish Carboniferous would form a valuable piece of research.[2]

(4) DISTRIBUTION OF COALS, OIL-SHALES, AND FIRECLAYS. (FIG. 8).

(a) Oil-Shales.[3] The principal Scottish oil-shales are indicated in Fig. 8. They occur, as will be seen, in the Calciferous Sandstone Series, and although strata of this age are well developed in many parts of Scotland, it is only in West Lothian, Midlothian and parts of Fife that oil-shales of economic importance are found. The typical Lothian oil-shale is a fine-grained, tough, and often flexible rock, with a black or brownish colour. It is minutely laminated and consists essentially of clayey material "containing or combined with widely varying quantities of organic matter of various

[1] They are very often referred to simply as "mussels."

[2] *See* p. 482. The reader should also consult Wheelton Hind's monograph on '*Carbonicola*, *Anthracomya* and *Naiadites*,' *Pal. Soc.*, 1894.

[3] A full account of the Scottish Oil-Shales (including Geology, Methods of Working, and Technology) is given in 'The Oil-Shales of the Lothians.' *Mem. Geol. Surv.*, 3rd Ed., 1927.

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kinds, to the oil-yielding portions of which the names 'Kerogen' and 'pyrobitumen' have been provisionally given."[1] It has a characteristic brown streak, and when cut with a knife the thin shavings tend to curl up. The ordinary shales which bulk so largely in the Carboniferous rocks are, on the other hand, much heavier and often gritty, and disintegrate rapidly on exposure to the weather. The oil-shale seams in the Lothians are numerous but vary greatly in thickness from a few inches up to 12 feet. Most of the valuable seams lie in the Upper Oil-Shale Group, above the Burdiehouse Limestone, and include the Camps, Dunnet, Broxburn, Fells, Mungle, Raeburn and Fraser seams; some distance below the Burdiehouse Limestone is the horizon of the valuable Pumpherston Shales. Lower still in the series are the thinner shales found at Dalmahoy, on the coast east of Queensferry, and at Granton. On the west side of the Midlothian Basin, at Straiton and Carlops, the higher shales are again present (Dunnet, Broxburn, Fells), but on the east side no workable seams have ever been found.[2] The main shale-field extends across the Firth of Forth into the Burntisland district where the Dunnet Shale, 4 to 7 ft. thick, was at one time extensively mined. Nowhere else in Fife, however, are workable oil-shales known.[3] Thin representatives of the two highest shales, the Raeburn and Fraser, have been recognised in the Strathaven district of Lanarkshire (Sheet 23).[4]

Gas coals and parroty or canneloid shales, occurring in higher subdivisions of the Scottish Carboniferous, have also been wrought as sources of oil at various localities. Some of these are noted in Fig. 8; they include the once well-known Lillie's Shale-Coal of the Paisley district, a compound seam of bituminous and cannel or parrot coal, occurring near the top of the Lower Limestone Group; the Lesmahagow Gas Coal in the Limestone Coal Group, once extensively wrought for gas-making and for oil-production, but now exhausted; the famous Boghead Cannel (Torbanehill Mineral)

[1] E. M. Bailey *in* 'Oil-Shales of the Lothians,' 1927, p. 158.

[2] Thin oil-shales are known, however, in the Calciferous Sandstone of the Cockburnspath (Cove Oil-Shale) and Gullane areas in Sheet 33. *See* 'Geology of East Lothian,' *Mem. Geol. Surv.*, 1910, pp. 47, 85.

[3] An 'oil-shale,' 10-13 in. thick, in the Calciferous Sandstone Series of East Fife, was worked on a small scale, about 1870, at Pitcorthie, near Crail.

[4] R. G. Carruthers, 'Carboniferous Sediments around Strathaven,' *Trans. Geol. Soc. Glasgow*, vol. xv, part 2, 1914, p. 162; or 'Economic Geology Central Coalfield, Area IX,' *Mem. Geol. Surv.*, 1921, p. 19.

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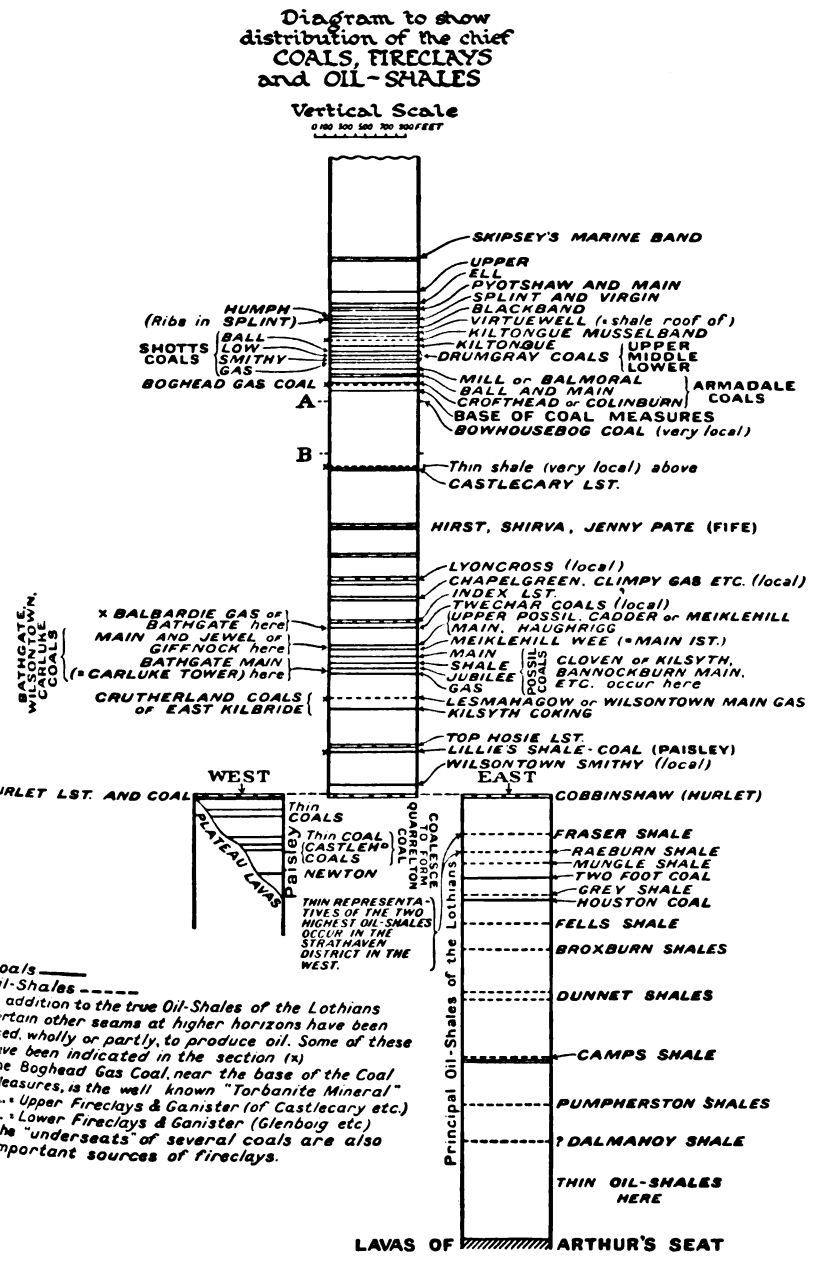


FIG. 8.

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found near the base of the Coal Measures in the Armadale district[1] (a few feet below the Colinburn Coal); and the shales associated with the Kiltongue Musselband and with the Virtuewell Coal. Many other cannels and shales throughout the Scottish Carboniferous have been worked locally on a small scale as oil-producers or have been tested for oil.[2] Most of these occur as compound seams in association with ordinary coal or with blackband or clayband ironstone and the cannel portion is, as a rule, variable and impersistent.

*Coals.* The principal coal seams found in the Central Coalfield are indicated in Fig. 8, and in addition a series of comparative vertical sections of the Limestone Coal Group and of the Productive Coal Measures of the main Scottish coalfields are given in Plates I, IA, II, and III. The varied nomenclature in use for the limestones has already been commented upon in an earlier section, and the difficulties are still greater when we come to the naming of the coals. Instances are known where the seam changes its name four or five times within a distance of a few miles. Thus in the Limestone Coal Group on the north-west side of the Central Coalfield the Upper Possil Coal of Glasgow is known as the Cadder Main Coal at Cadder, as the Meiklehill Main at Kirkintilloch, and as the Haughrigg at Kilsyth. In the same group in Fife the Milton Main of Valleyfield is the same seam as the Three Foot of Blairhall, the Ontake of Comrie and Oakley, the Fourteen Foot of Dunfermline, the Bright of Townhill, and the Rough Coal of Kelty, Glencraig and Bowhill. The same thing happens in every coalfield and there is no need to multiply examples. The comparative vertical sections (Plates I to III) show the seams present in the main coalfields and the names most commonly in use, and these sections will serve to illustrate the very varied nomenclature. The names used may be derived from place-names (farms, etc.)

[1] This was the material selected by Young in 1850 as the most suitable for his new method of producing oil by distillation. The Boghead Cannel was worked up to 1861 when the seam was exhausted, but about 1858 another material became available through the discovery, in the Broxburn district, of oil-shale deposits.

[2] e.g. the Lochgelly Parrot, and the shale associated with the Lochgelly Blackband, both occurring in the Limestone Coal Group of Fife; Earl David's Parrot of Wemyss and the Westfield Shale of Auchterderran in the Productive Coal Measures of the same county; the Arniston Parrot near the base of the Limestone Coal Group of Midlothian, etc., *see* 'Cannel Coals, Lignites and Mineral Oil in Scotland,' *Mem. Geol. Surv.*, 1922.

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like Drumgray, Virtuewell,[1] etc.; or they may be descriptive of the quality or thickness of the seam, like Splint,[2] Gas, Six Foot, or Ell;[3] or they may be more general designations like Main, Wee or Upper. Several coals at widely separated stratigraphical levels are known under such names as "Main Coal," or "Ell Coal," and when we find seams referred to as "Five Foot Coal," "Three Foot Coal," etc. occurring similarly at different horizons throughout the coalfields the problem of correlation becomes somewhat

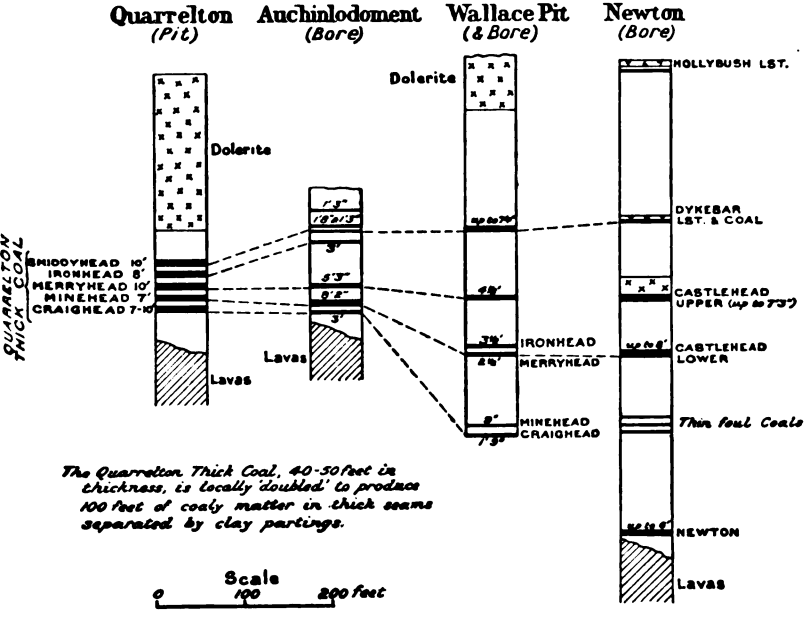


FIG. 9.

involved. These difficulties of nomenclature are due partly to historic reasons, the seams being named independently in the areas where they were first worked, and partly to actual difficulties in establishing definite correlations. One source of difficulty lies in the tendency of many coals to split up into two or more leaves,

[1] An old Holy Well, situated about half a mile north-west of Commonhead Station, Airdrie, has provided the name 'Virtuewell."

[2] A hard coal with a dull lustre and uneven fracture which does not cake or break up readily in a furnace.

[3] An old measure for cloth, 1¼ yds. in length. The Scottish ell is said to have been slightly over 37 in.

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continue for some distance as separate seams, and then perhaps coalesce again. Thus in the North Ayrshire Coal Measures, the Hurlford Main splits up into the Parrot, Turf, and Wee, the Five-quarter into the Darroch and Whistler. In the same group in Lanarkshire the Pyotshaw and Main may form one seam or may be separated by as much as 42 ft. of strata; the Splint and Virgin similarly may be separate or conjoined; while such coals as the Ell and Kiltongue again occur locally in bands. The Jersey coals of the Limestone Coal Group of Fife also offer an instructive example of splitting and of variability in the thickness of the strata separating the constituent seams. A special case of the kind has been described from the Paisley district where the Quarrelton Thick Coal, lying low down in the Upper Calciferous Sandstone sediments,[1] attains a thickness of 40 or 50 ft. through the coalescence of several seams well-separated elsewhere in the district.[2] The mode of origin of the thick Quarrelton Coal is illustrated in Figure 9.

Another source of difficulty is due to the thinning out of coal seams. A workable coal in one area may thin away in an adjoining area to a few inches, or may be entirely absent (*cf.* p. 542). In the little Kinglassie field of Fife, for example, there occur in the lower part of the Productive Coal Measures thick beds of coal and coaly material, most of which are of merely local occurrence (Fig. 10). The Bogside Main Coal together with the seams overlying it (65 ft. of coal in 80 ft. of strata) appear to correspond to the Dysart Main of the Dysart-Wemyss coalfield. The Limestone Coal Group at Kilsyth, 1200 or so ft. thick, contains 14 or 15 workable coals, but at Stonehouse, where the thickness of the whole group is about 270 ft., only six or seven, usually thin, seams are present. The question of the correlation of our coals forms however, the subject of a later section of this paper and need not be further referred to here.

The two great repositories of valuable coals in Scotland are the Productive Coal Measures (Plate III) and the Limestone Coal Group (Plates I, IA and II). Coal seams occur however in every subdivision of the Carboniferous rocks. Thus in the Calciferous Sandstone Series of the Paisley district we have the Newton,[3]

[1] Below the Dykebar Limestone; *see* Fig. 7.

[2] 'Economic Geology Central Coalfield, Area IV,' *Mem. Geol. Surv.*, 1920, pp. 19-28. At two localities doubling of the seam takes place and a total thickness of 100 ft. of coal, or coal with thin clay partings, is attained.

[3] This is the lowest seam ever worked in the West of Scotland.

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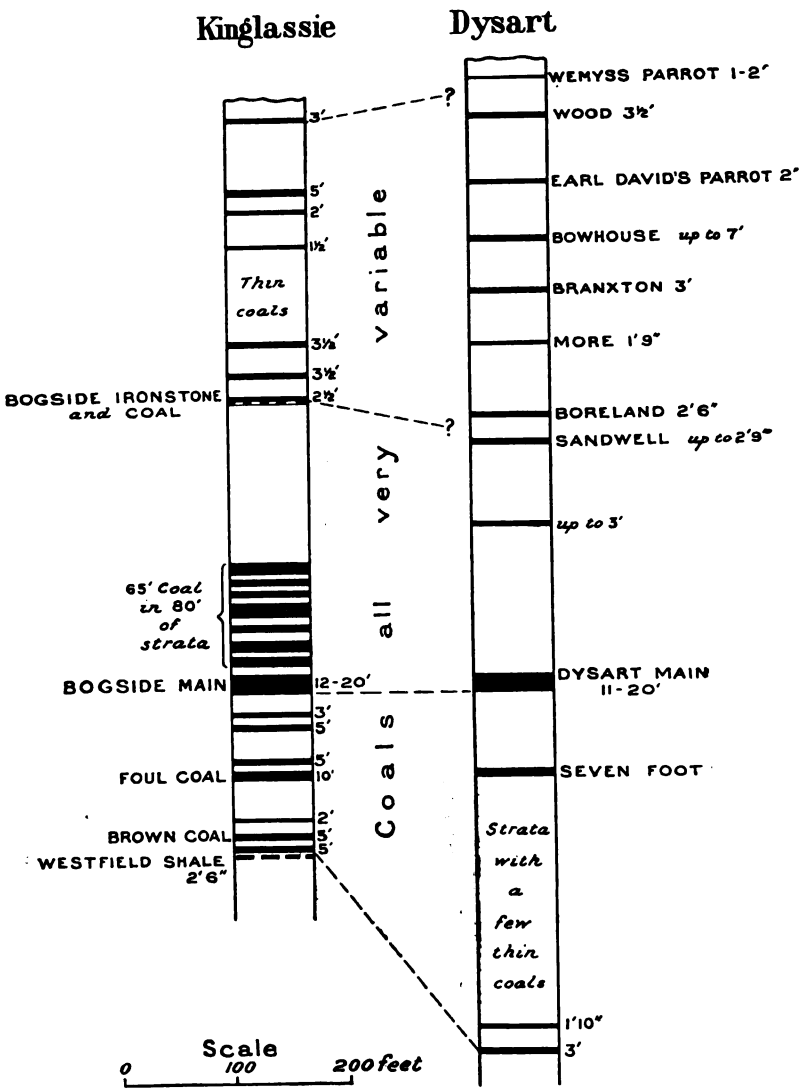


FIG. 10.



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Castlehead and Quarrelton Thick (see Fig. 9) coals; in the Upper Oil-Shale Group the Two Foot and Houston seams; and in the Calciferous Sandstone of East Fife the two Kellie seams once worked to some extent in the country north and south of Carnbee.[1] At various localities in the neighbourhood of Edinburgh coals, 1 ft. or more in thickness, have been found in the Wardie Shales[2] and are probably the equivalent of the seams (up to 9 inches), met with in the "Carbonaceous Group" of East Lothian (*see* p. 496); the latter in turn are represented farther south by the Lawston Linn or Lewis Burn coals of Liddisdale[3] and by part of the Scremerston Coal Group of North Northumberland. In the Lower Limestone Group again a number of seams have been worked locally at one time or another. These include the Hurlet Coal below the Hurlet or Main Limestone;[4] the North Greens Coal of Midlothian, a little below the North Greens Limestone (p. 521); the Vexhim Coal of Loanhead and Niddrie in the same field, below the Lower Vexhim Limestone; and the Lillie's Shale-Coal (p. 532) of the Paisley district, in the middle of the Hosie Limestone group. The Upper Limestone Group also contains a number of coals, some of which have been locally wrought. Among these may be noted in the Central Coalfield the Chapelgreen Coals (1 to 2 ft. thick) of Dumbreck and Meiklehill in the Kilsyth area (Sheet 31), between the Index and Lyoncross limestones; the Arden, Hirst or Shirva Coals, below the Calmy Limestone. The Upper Limestone Group in Midlothian includes the South Parrot Coal, between the Index and Extra (= Orchard) Limestones and the Wood Coal between the Extra and Calmy Limestones; while in Fifeshire the same group contains the Lochore Parrot, a little below the Lyoncross Limestone, the Capeldrae Parrot, below the Orchard Limestone, and the Jenny Pate or Craig Coals, below the Calmy Limestone.[5] The

[1] i.e. the "Fore" and "Back" seams; *see* 'Geology of Eastern Fife,' *Mem. Geol. Surv.*, 1902, pp. 116-118.

[2] D. Tait, 'The Rocks between Leith and Granton, with Historical Notes on the Working of the Wardie Coal,' *Trans. Edinb. Geol. Soc.*, vol. xi, part 3, 1925, pp. 346-351.

[3] The thickest coal in this group is 1½ to 2 feet thick; it was at one time extensively wrought.

[4] The limestone and coal are sometimes regarded as together constituting the Hurlet Seam and forming the lowest member of the Lower Limestone Group. At Hurlet and Nitshill, 3 miles S.E. of Paisley (Sheet 30) the coal averaged 5½ feet; it has also been worked at a number of other localities.

[5] The Jenny Pate Coals correspond with the Arden or Hirst Seams of the Central Coalfield.

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Millstone Grit, although remarkably rich in fireclays, carries, as a rule, only a few very thin coals; but at one horizon in the upper part of the Series in the Central Coalfield, occurs a very variable and impersistent seam which has been found thick enough to work locally on a small scale (Bowhousebog Coal).

There are of course many thin seams of coal throughout the Carboniferous of Scotland in addition to those noted above or recorded in the sheets of comparative vertical sections attached.

An interesting feature of the distribution of the valuable coals in the Productive Coal Measures is the evidence for a rise in stratigraphical level as they are followed from north to south. These measures in the Dysart-Wemyss field show a division into two sub-groups; (1) a lower sub-group, about 845 ft. in thickness, from the base of the Coal Measures up to the Parrot Coal, and (2) an upper sub-group, 570 ft. thick, from the Bush Coal up to the marine band at the top (Plate III, Section 10). The thickest coals occur in the lower sub-group, and, taking the principal seams alone into consideration, we find in it a total thickness of about 47 feet of coal, as compared with approximately 28 feet for the upper sub-group. In the Midlothian basin again there is a similar division into an upper series of coals, the Craighall Coals, and a lower series, the Brunston or Cowpits Coals; the upper series is confined to the northern part of the basin and shows for the principal seams a total thickness of coals of about 28 ft. at Craighall, decreasing eastwards to about 20 ft. at Dalkeith; the lower sub-group shows for its chief seams, on the other hand, a thickness of coal varying from 40 to 34 feet on the west side of the field (Craighall) and decreasing eastwards to about 25 feet (Cowpits). The two sub-groups are separated by about 200 feet of relatively barren strata. In the Central Coalfield there is a higher group of coals, from the Splint upwards, and a lower group comprising all the seams from the Virtuewell down to the Colinburn; the interval between the Splint and Virtuewell may be taken as approximately 170 feet. The lower coals, which include the Drumgray and Armadale seams, are best developed on the east side of the coalfield in the Fauldhouse, Armadale and Falkirk districts, but thin out westwards and south-westwards. In the Falkirk field the chief seams in this lower group show a total thickness of coal of about 25 feet, but in the Airdrie and Wishaw districts only 15 or 16 feet; the figure is still lower for the Rutherglen, Quarter and Larkhall fields. The upper group, on the other hand,

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shows for the principal seams a thickness of coal of 24 feet at Coneypark, 22 feet at Airdrie, 27 feet at Wishaw and 22 feet at Rutherglen and Larkhall. This group therefore is now taking predominance. In the Kilmarnock district of North Ayrshire again there are an upper and a lower division of the Productive Coal Measures, corresponding to those of the Central Coalfield and separated by an interval of about 100 feet; here also the principal seams are in the higher group while those of the lower group are more variable. In the Douglas Valley coalfield the same phenomenon is manifest, the upper group containing the thicker and more valuable coals (Nine Foot, Four Foot, Three Foot and Seven Foot), the lower group the thinner and more variable seams. As the Productive Coal Measures therefore are followed from Fife into Ayrshire there is a gradual but definite change in the relative proportions of coal in the two groups; the lower group is the more productive in the north-east, while in the south-west and south of the Central Coalfield, in the Douglas Valley and in North Ayrshire the conditions are reversed. The difference might be stated in another way; in Fife and Midlothian the valuable seams are mainly of Lower Lanarkian age (p. 464) while farther south-west they are dominantly Upper Lanarkian. We can however, carry the rise in stratigraphical level a stage further. In Central Ayrshire (Coylton, Mauchline, etc.) there is a strong development of the upper coals of the Productive Coal Measures (the Three Dirt, Crawfordston and Ell seams) but at a height of about 30 feet above the Ell the grey coal-bearing strata cease and the red-coloured sandstones and marls characteristic of the Barren Red Measures begin. In Southern Ayrshire on the other hand (Polquhairn, New Cumnock, Dalmellington, etc.) coals extend upwards throughout a distance of no less than 420 feet above the Ell; in this interval there may be as many as eight coals, varying in thickness between 1 and 3 feet. At New Cumnock it has been shown in addition that the grey measures with coals extend upwards to 265 feet above Skipsey's Marine Band. The dividing line between Lanarkian and Westphalian (or Yorkian) was drawn by Kidston at the horizon of the Lanarkshire Ell Coal; the seam can with some confidence be identified with the McNaught Coal of North Ayrshire and this in turn is correlated with the Ell of Central and South Ayrshire. In South Ayrshire therefore the coals present above the Ell would seem to be of Westphalian age. Certainly nowhere else in the Central Valley

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of Scotland do the beds above Skipsey contain such a marked development of grey coal-bearing strata. Farther south still in the Canonbie field the Coal Measures have been divided into Lower Coal Measures, Middle Coal Measures and Upper Coal Measures (*see* p. 452). The first group contains the Rowanburn Coals[1] with seams varying from 3½ to 9 feet, and is referred to the Lanarkian; the Middle Coal Measures contain the Byreburn Coals, with seams ranging from 3 to 5 feet, and are placed in the Westphalian; the Upper Coal Measures consist of red sandstones and marls with some thin coals near the base, and on the evidence of the fossil flora have been compared, in part at least, with the Keele Group of the North Staffordshire area.[2] In the English Midlands the chief seams of coal are concentrated in the Middle Coal Measures and are thus Westphalian in age.

The coals in the Scottish Carboniferous appear to have been all formed *in situ*. Lenticles and streaks of coal or coaly matter are of very common occurrence in the various sandstones but there is no evidence to show that actual seams have been formed by drifted material. There is always something of the nature of a seat-earth with rootlets. The occurrence of such a great mass of coal as the " doubled " Thick Coal of Quarrelton (p. 536) is a purely local phenomenon and has been ascribed to something of the nature of a ' bog-slide '[3]—the slipping of the material from a higher to a lower level on the margins of the marsh in which it was accumulating.[4]

## VI. CORRELATION OF COALS.

The sheets of comparative vertical sections forming Plates I-III have been prepared with a view to showing how far correlation can be carried from one coalfield to another. This question of correlation is nowadays receiving more and more attention and is certainly one of great economic importance. If a series of investigations are carried out on the physical and chemical properties of the coals of a particular area and these are classified

[1] Some of these have been extensively worked.

[2] For the position of the Keele Group in Kidston's classification *see* p. 463.

[3] *See* R. G. Carruthers in " Economic Geology Central Coalfield, Area IV," *Mem. Geol. Surv.*, 1920, pp. 22-25.

[4] Doubling of coal seams along the edges of contemporaneous river-courses (" wash-outs " or " wants ") is not uncommonly met with in mining operations in Scotland. *See*, for example, *Trans. Mining Institute of Scotland*, vol. vi., p. 235.

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according to their suitability for different industrial and manufacturing purposes, it is obviously desirable to know if the same seams can be identified in adjoining fields. Any survey of our coal resources which aims at something more than a rough estimate of reserves, which aims, that is, at submitting the coals to a series of standard tests and at classifying them according to the results of these, must deal with the question of correlation at the outset. If, for example, we are investigating the properties of the Upper Drumgray Coal it is important to know that it is the equivalent of the Furnace or Ball Coal of Shotts, of the Splint of Falkirk, of the Main of Carron, or of the Alloa Splint of the Clackmannan field, and that in certain areas the seam wrought under the name 'Upper Drumgray' has been wrongly so-called. It is important to know that the Coking Coal of Kilsyth is the Milton or Lower Knott of Denny; that it thins away when followed in a south-westerly direction and over the Glasgow area, south of the Clyde, and in North Ayrshire is represented by a coal less than a foot thick; that it probably corresponds in the Wilsontown field to the seam known as the Haywood Under Coal; and that in the Bo'ness and West Fife districts its equivalent is to be found in the group of coals which include in the one case the Easter Main and in the other the Dunfermline Splint. It is important to know the area over which a coal extends as a workable seam and to ascertain if the properties which make it valuable in one area hold for its equivalent in other fields. It is important again to know what seams are liable to splitting, what seams have a wide distribution or which ones on the other hand are comparatively local in their occurrence. There are several coals for example in the Loanhead sequence of Productive Coal Measures (Midlothian Basin) which are not present a little farther south at Mauricewood.

It is to facilitate research of this kind that the accompanying tables have been constructed. They indicate the extent to which correlation of the different coalfields can be carried out with the information at present available; but they show also clearly the difficulties that have to be faced. Even to-day there is much misconception in regard to this question. I have sometimes been asked to set down the important coals in our Scottish coalfields in their proper geological sequence. It might be possible to do this for groups of coals, but quite impossible if we are dealing with individual seams, and this is true, not only for correlations between different coalfields, but also, in many cases, for corre-

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lations between different parts of the same coalfield. The coalfields are too much interrupted and disconnected, and the variations in the thickness both of the coals themselves and of the strata associated with them are too great to allow of such close comparison throughout. Nevertheless important advances have been made in recent years in correlating important horizons and every new boring or fresh underground development provides additional evidence. The problem is certainly not one of merely academic interest. We wish to know the properties of the valuable coals in our coalfields, how to make the best use of them, and especially to know how to treat them and what to extract from each in the way of gas and crude oil before they are finally used as fuel. We have been compelled during the post-War years to conserve our coal resources whether we wished it or not, and the problem before us is not wholly one of increasing the output but of utilising what is produced in the most economical way. And if a physico-chemical survey of our coals is undertaken it seems essential to begin with a detailed study of their distribution such as I have attempted. I should like to go farther than this even and venture to make the following suggestions:—

(a) All our worked or workable seams should be classified according to their geological position in the coalfields in which they occur.

(b) Each seam should be assigned the name under which it is most widely known, but a list of synonyms should also be added.

(c) The outcrop of each seam, where proved, should be laid down on a special set of six-inch maps and the conjectural continuation of the outcrop added.

(d) The worked-out areas of each seam, wherever these are known, should be added to the maps and brought up to date from time to time as the working proceeds.

(e) Outside the worked areas any data from borings regarding the thickness and depth of the seam should also be put upon the maps.

In this way we should have a fairly complete account of each seam showing the area it occupies, the worked-out and the unworked portions, and its thickness and depth at various points throughout these latter.

(f) Records should also be kept of proved sections of each seam, of any variations in its thickness or character, of the nature of any ribs it may contain, of variations in the floor or roof, or of any lithological or palaeontological peculiarities in the strata associated with it which may serve as a means to identify it in unproved ground.

(g) Records of any tests made of the physical or chemical qualities of the seam should also be carefully kept, and wherever possible the positions at which the samples for examination were collected should be indicated on the maps.

A scheme of this nature would certainly furnish a statement of

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our coal resources which could be adjusted and brought up to date from time to time.

*Criteria used in establishing correlations.* What are the criteria made use of for the purpose of establishing detailed comparisons? Let us take the case of a boring put down through a series of sandstones, shales, limestones and coals, whose position in the geological sequence we are asked to fix. We have, of course, at our disposal the records of the many borings already put down in the Carboniferous rocks, and where the materials from these have been carefully examined by competent observers we have a description of each bed proved and an account of the lithological character and palaeontological contents. It is by close comparison with these records that we approach the problem in the first place. The criteria made use of may be listed as follows:—

(a) Relation to one of the well-established index-horizons. The principal index-horizons have already been dealt with in an earlier section of this paper and it is clear that if we can fix even approximately the position of the beds in question by reference to one of these we have gone a long way to establishing a correlation. The position of the index-horizon relative to the boring may be known or inferred from the general geological structure of the ground.

(b) Lithological sequences. These are very often of the greatest service as a means of comparing the strata in adjoining areas. For this purpose each bed must be taken separately and examined, and the characteristic features and thickness of each carefully recorded. It may be of ultimate value for purposes of close comparison to note for example in the case of sandstones the approximate composition, the texture and colour, signs of bedding and the presence or absence of partings or joints. In the case of shales it may be useful to know if they are blue-black, crumbling and poorly bedded, or black, hard and fissile, if they are markedly bituminous or not, or if they contain ferruginous or calcareous lenticles; and in the case of fireclays whether they are sandy or not, whether they are bright-coloured or charged with carbonaceous matter. The strata must be gone over bed by bed and any characters noted that may help correlation with other sections.

(c) Fossil evidence. The value of fossils for correlation purposes varies very much. Marine limestones or shelly blaes are of fundamental importance owing to the fact that they persist as a rule over relatively wide areas. Of less importance are the *Lingula* bands, the 'mussel' bands of the Coal Measures (*Carbonicola*, *Naiadites*, etc.) and the various 'fern' and 'fish' beds that have been discovered throughout the Carboniferous succession. Fossil evidence of any kind is worth recording; it has always some immediate value for correlation purposes, and records that at present seem of little importance owing to our imperfect knowledge regarding the distribution of many forms of life may eventually prove of diagnostic value. Faunal assemblages and faunal successions are

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often useful guides to position; the occurrence of a *Lingula* or a *Naiadites* band overlying a marine horizon may be instanced as an example of the latter.

It may be necessary to utilise all these criteria before we can reach a solution of our problem and it is only by such detailed examinations carried out foot by foot that we can continue our correlation lines from one boring to another, and from one area into another, and show in what direction and to what extent changes in sedimentation have taken place. The difficulties that face anyone who attempts a close comparative examination of our productive measures may be readily understood by a study of accompanying sheets of vertical sections (Plates I-III).

One example of the value of detailed correlation of this kind may be given. Portions of the journals of two borings, half-a-mile or so apart are here shown in graphic form (Fig. 11).

The limestones at the top of the two sections are known from their character, associated strata and fossil content to be the same (i.e. Lyoncross Limestone). The upper half of section (2) agrees closely with that of Section (1), but below this there is a marked discrepancy. On the other hand the lower half of Section (2) can be matched bed for bed with strata found in No. 1 bore between 647 and 822 feet. The beds proved in Section (1) but omitted in the figure amount to a little over 500 feet and accordingly we are able to say that in Section (2) there is a fault at the point B of approximately 84 fms. We are also able to say exactly what coal seams Section (2) has failed to prove. This result could only have been arrived at by a close comparison of the two sections, bed by bed.

Tables showing the results of the examination of the information at present available for the two productive subdivisions of the Scottish Carboniferous are appended to this paper. It will be remembered that the Scottish coalfields are strung out along the Midland Valley in a north-east—south-west direction and are broadly classified into:—

(a) Coalfields of Fife; including the Productive Coal Measures of the Dysart-Wemyss field, and the Limestone Coals of Central Fife (Cowdenbeath, Lochgelly, Kelty, etc.) and of West Fife (Oakley, Saline, etc.).

(*b*) The Stirling-Clackmannan Coalfield, including the small basins of Coal Measures in the Alloa-Dollar district and the Limestone Coals of Bannockburn and Polmaise.

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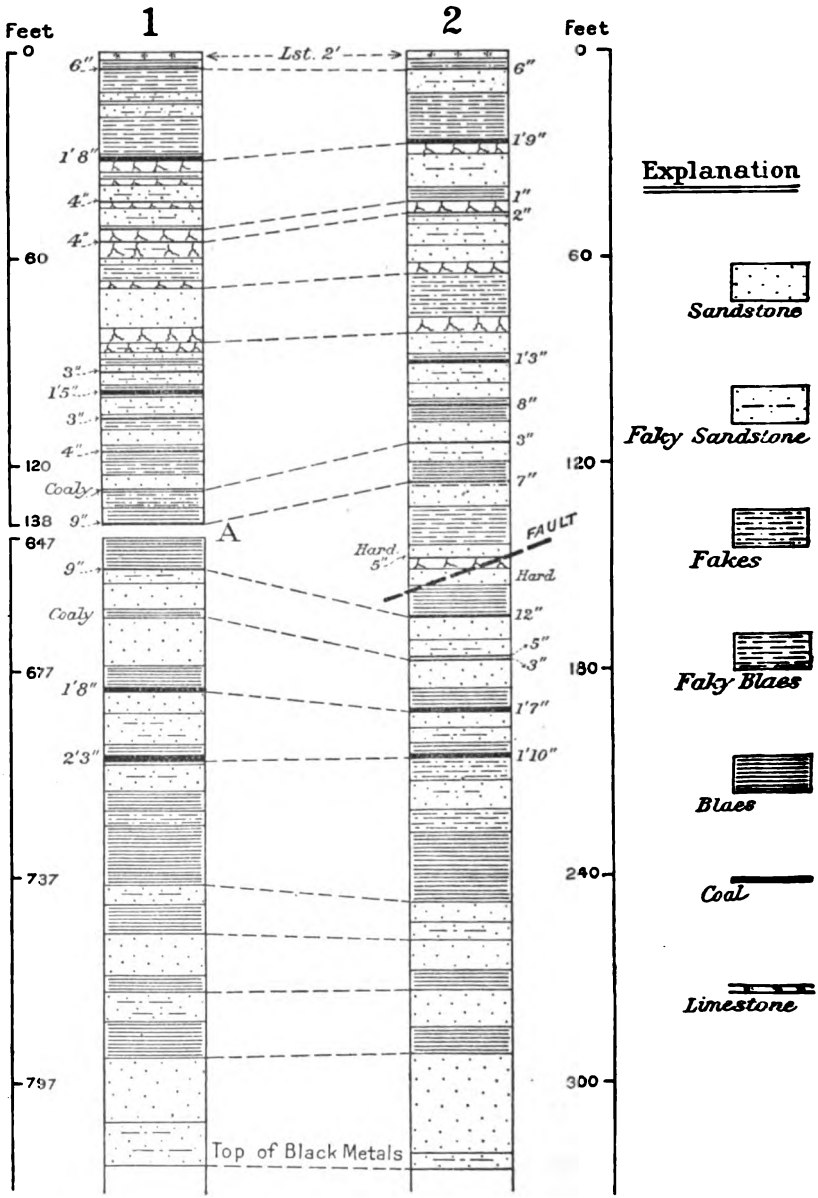


Fig. 11

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(c) Central Coalfield. The main unit here is the great Lanarkshire basin with its broad inner area of Productive Coal Measures centred around Coatbridge, Hamilton and Wishaw, and extending north-eastwards into the Falkirk, Armadale and Fauldhouse fields; and with its fringe of Carboniferous Limestone strata in the Denny-Kilsyth-Kirkintilloch-Cadder fields on the north-west, the Bathgate-Wilsontown fields on the east, and on the south the less important fields around Carluke, Auchenheath and East Kilbride.

(d) The Ayrshire Coalfields, very variable as regards productivity, and subdivided in turn into northern, central and southern fields. In North Ayrshire are the Limestone coals of the Kilbirnie and Dalry district, and the Coal Measures coals of Kilwinning, Kilmarnock and Galston; in Central Ayrshire a wide basin of Carboniferous rocks fringing and underlying the New Red sandstones and lavas of the Mauchline Basin; in South Ayrshire the Limestone Coals of New Cumnock, Muirkirk, Patna and Dailly, and the Productive Coal Measures of Lugar and Dalmellington.

(e) The Lothian Coalfields, consisting of an area of Carboniferous rocks extending along the Firth of Forth for about eight miles between Portobello and Port Seton and stretching inland for a maximum distance of nearly twenty miles. An anticlinal axis running from Prestonpans to Gorebridge separates the area into two parallel troughs, the western one forming the deep Midlothian basin,[1] the eastern one the much smaller and flatter Haddingtonshire basin. The Coal Measures of Midlothian are continued across the Firth of Forth into the Dysart-Wemyss field.

(f) Minor Coalfields; Douglas Valley, Sanquhar, Campbeltown and Canonbie. The first-named contains both Coal Measures and Limestone Coal Group coals but on the southern and south-eastern margins of the Carboniferous area there is some evidence to show that the Millstone Grit overlaps the Upper Limestone and Limestone Coal groups successively and comes to rest almost directly upon the Main (or Hawthorn) Limestone, the lowest member of the Lower Limestone Group (*see* p. 462). The coals of the Sanquhar-Kirkconnel field (Sheet 15) belong to the Coal Measures. Taking the New Cumnock and Sanquhar areas together there is the clearest evidence of marked overlap on to the old rocks of the Southern Uplands. In the Gatelochside and

[1] The Limestone Coal Group is over 400 fms. deep at the northern end.

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Burnton burns, 1½ miles east of New Cumnock, for example, Mr. J. B. Simpson has shown that the Limestone Coal Group rests unconformably on Ordovician strata. In the Sanquhar field again the Coal Measures have been mapped as directly overlying the Silurian.[1] It should be noted, however, that in the Kello Water strata tentatively referred to the Millstone Grit form a narrow zone between the Coal Measures and the older rocks; they include a bed which has a close lithological resemblance to parts of the well-known Ayrshire Bauxitic Clay.[2] The Campbeltown coalfield is of Limestone Coal Group age and the strata present here include representatives of the Upper Limestone Group and of the Millstone Grit volcanic rocks of the North Ayrshire province. In the Canonbie district a very full development of the Carboniferous is present (*see* p. 452).

The distribution of the principal Scottish coalfields is an expression of the folding—mainly along north-east—south-west axes—to which the Carboniferous rocks have been subjected as a result of crustal movements, and of the denudation that has since taken place. Moreover, in each of the main fields listed, folding and faulting have produced a number of more or less separate basins or mining fields, and it is to this complex system of folds and faults that our difficulties of close correlation are in a large measure due. Cases have occurred where different coals have been worked in adjoining areas under the same name; in other cases again a seam has been worked up to some dislocation and an entirely different coal opened out and wrought as its continuation across the fault. Errors of this kind could be avoided by a careful examination of the strata associated with each seam and by a detailed comparison bed by bed. On the other hand there are areas where in addition to folding and faulting other factors come into play; there may be splitting of coals, and a coal in one field may be represented by a group of coals in another; there may be rapid and marked attenuation of the strata in a certain direction; there may be changes in sedimentary facies, a sandstone passing laterally into sandy shales, a limestone into shelly blaes. All these factors, folding, faulting and variations in the character or amount of the sediments, create difficulties when we attempt to carry correlations too far. It would be impossible, for example, to find

[1] Geological Survey One-inch Map, Sheet 15, 1870; 'Explanation' 1871, p. 32.

[2] *See* 'The Ayrshire Bauxitic Clay,' *Mem. Geol. Surv.*, 1922, p. 24.

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equivalents for all the coals in the Limestone Coal Group of Kilsyth in the much attenuated representatives of the same subdivision found at Carluke or in Ayrshire. All we can do is to indicate the approximate area over which a particular coal can be traced. Accordingly the tables appended show both the extent to which correlation can at present be safely carried and the limits that must be set to it.

## VII. CORRELATION TABLES.

Three sheets of comparative vertical sections of the Limestone Coal Group (Plates I, Ia and II) have been prepared and one of the Productive Coal Measures (Plate III). The sections selected show the thickness of these two important subdivisions at different parts of the principal coalfields, the chief coal and ironstone seams in their proper sequence, and the names under which these are locally known; proved and tentative correlation lines have also been added. Imperfect though the tables are they yet provide the most complete comparative statement that has so far been attempted. They will be of service in fixing the relative geological position of the worked and workable coals, in showing how far particular seams can be followed, and in assessing the productive capacity of the different coalfields.

### (1) Productive Coal Measures (Plate III).

In the Central Coalfield the area occupied by Productive Coal Measures is almost wholly a continuous one; part of it forms the concealed coalfield of the Clyde Valley, underlying the Barren Red Sandstones of the Hamilton-Uddingston-Bothwell district. In addition a narrow faulted inlier of Coal Measures is found at Banknock and Dennyloanhead. Throughout this tract, where mining and boring have been in progress for many years, correlation is usually a relatively simple matter, provided we check our steps by constant reference to the varic us sources of information at our disposal—natural sections, borings, shaft sections and underground workings. The workable coals fall into two groups: (1) an upper group of thick coals (Splint to Upper) confined mainly to the south-western part of the coalfield,[1] and (2) a lower group (Virtuewell to Colinburn) with a much wider distribution.

[1] This group is also represented in the Banknock field (at Coneypark and Dennyloanhead). *See* "Economic Geol. Central Coalfield, Area II," *Mem. Geol. Surv.*, 1917, p. 47.

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This lower group includes the Drumgray and Armadale Coals, the latter developed as workable subjects only in the eastern and north-eastern parts of the field (Shotts, Fauldhouse, Armadale, Falkirk, etc.). Perhaps the most useful index-horizon for these measures is the Kiltongue Musselband, a compound seam of shale and ironstone overlying a thin band of shale crowded with crushed *Carbonicola* shells; bands of estuarine lamellibranchs (" mussels ") occur at various other horizons (Fig. 7 and p. 531) but these appear, so far as our present knowledge goes, to have a more restricted distribution. We have to depend for detailed correlations very largely upon lithological sequences helped out by what confirmatory evidence can be obtained from the occurrence of beds containing fossil remains—" mussels," plants or fish.

The correlations that have been established within the Central Coalfield are shown in Plate III, Sections 4 to 8.

In the case of the Productive Coal Measures of Ayrshire it is possible to correlate a number of the important coals of the Kilmarnock-Kilwinning area with those in the central and southern fields (Plate III, Sections 1 to 3). Thus the McNaught Coal of Kilmarnock is the equivalent of the Bowbrig of Kilwinning and of the Ell of Ayr and Dalmellington. The Five-quarter coal (Plate III, section 2) corresponds to the Finnie's Main which splits up eastwards into the Darroch and Whistler. The Hurlford Main of Kilmarnock again is represented in the Stevenston-Irvine country by three seams, the Parrot, Turf and Wee; its equivalents farther south are the Hard Coal of Ayr, the Splint of Coylton, the Maids of Lugar and the Chalmerston of Dalmellington.

It is when we come to compare the main Scottish coalfields, however, that our evidence begins to fail. The North Ayrshire area of Coal Measures is separated from that of the Central Coalfield by a distance of 15 miles. A few tentative correlations may be made (Plate III, Sections 3 and 4) but there is no reliable index horizon common to both. The chief point of comparison lies in the presence in both fields of an upper persistent group of coals and a lower more variable group separated by a relatively barren interval.

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| | *North Ayrshire* | *Central Coalfield* |
|---|---|---|
| Upper Group | McNaught to Wee | Ell to Virgin |
| Barren Group | between Wee & Shale | between Virgin & Virtuewell |
| Lower Group | Shale downwards | Virtuewell downwards |

The Ell of Lanarkshire is tentatively correlated with the McNaught of Ayrshire, the Splint and Virgin with the Hurlford Main, and the Virtuewell with the Shale.

Too little is known of the upper seams at Alloa to allow us to identify their exact equivalents farther south, but a fairly close comparison of the lower coals can be made with those of the Central Coalfield. The correlations established are shown below (*see also* Plate III, Section 9):

| *Lanarkshire* | *Carron & Airth* | *Alloa* |
|---|---|---|
| Kiltongue | Crow | Alloa Cherry |
| Upper Drumgray | Carron Main | Alloa Splint |
| Lower Drumgray | Upper Coxrod | |
| Shotts Gas | Lower Coxrod (=Airth Upper) | Coalsnaughton Main (=Hawkhill Splint) |
| Mill (=Balmoral of Coatbridge) | Auchingane (=Airth Ball) | Mid-Cherry or Mill (=Tulliallan Splint) |
| Main | Glenfuir (=Airth Main) | Lower Splint or Ball (=Hawkhill Main) |
| Colinburn (=Crofthead) | Colinburn | Two Foot Splint of Hawkhill. |

The Alloa field is separated from that of Dysart and Wemyss by a distance of twenty miles and no satisfactory correlations between the two have yet been made. Neither have definite correlations been established between the Fifeshire and Midlothian fields, connected as they are across the Firth of Forth, nor between the latter and the Lanarkshire field. We must wait for evidence bearing on the question until the distribution and range of the non-marine lamellibranchs have been thoroughly worked out. Both Fifeshire and Midlothian show, as in the case of the Central Coalfield and Ayrshire, two groups of coals separated by a comparatively barren interval; in Fifeshire the upper group includes the Chemiss, Six Foot, Eight Foot and Wall, and the lower group, the Wemyss Parrot, Earl's Parrot, Bowhouse, Boreland, Sandwell, Dysart Main and Lower Dysart (Plate III, Section 10). In

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Midlothian similarly there is an upper group of coalst, the Craighall Series, and a lower group, the Brunston or Cowpits Series, separated by 200 feet of strata (*cf.* p. 539).

In the Coal Measures of the Douglas Valley again an upper group of thick coals, including the Nine Foot, Four Foot, Three Foot and Seven Foot seams, is separated from a lower series of thinner and more variable seams (wrought at Inches) by about 120 feet of strata. The Nine Foot coal here is possibly the equivalent of the Lanarkshire Splint.

(2) Limestone Coal Group.

Reference to Plate I, Sections 1 to 3 and 5 to 8, will show how this group varies in thickness throughout the Central Coalfield. It attains a maximum in the Kilsyth district (1200 to 1300 feet) on the north-west side of the basin, is very considerably thinner on the eastern margin between Bathgate (760 ft.) and Wilsontown (600 ft.), and shows a still more marked attenuation along the southern edge in the Carluke (415 ft.), Stonehouse (270 ft.) and East Kilbride (480 ft.) fields. It underlies the wide central area of Coal Measures in the Lanarkshire basin but not very much is known of its development throughout this concealed tract. Two very valuable and constant index horizons are provided by the usually thick series of shales and ironstones known as the " Black Metals " which occurs near the middle of the group, and by the Johnstone Shell Bed, an easily recognisable marine band present between the Black Metals and the Top Hosie Limestone (*cf.* p. 488). The Black Metals vary in thickness from 20 to as much as 120 ft. and the associated clayband ironstones have locally proved thick enough to work. Different names given to the ironstones are as follows:—

| | Shales | Ironstones. |
|---|---|---|
| Kilsyth | Black Metals | Banton Claybands. |
| Glasgow | | California Claybands. |
| Wilsontown | | Hogg Fence Ironstones. |
| Carluke | | Maggie[1] Bands. |
| Auchenheath | Long Tills | Maggie Bands. |

The following correlations in the lower part of the Limestone Coal Group may be given:—

(a) The Lower Garscadden or Ibrox Blackband of Glasgow is on the same horizon as No. 4 Blackband of Twechar and the

[1] I.e. poor in quality; *cf.* French ***maigre.***

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Banton Blackband of Kilsyth. It is very probably represented on the east side of the basin by the Wilsontown Gas Coal. This in turn can be identified with the Lesmahagow Main Gas Coal and with the Earnockmuir Blackband of the East Kilbride field.

(b) The Kilsyth Coking Coal is represented in the Bannockburn field by the Lower Knott or Milton Coal and is perhaps to be correlated with the coal known at Wilsontown as the Haywood Under Coal. It is important to note that this valuable seam thins as it is traced outwards from the Kilsyth-Kirkintilloch area (Plate IA, Sections 9, 10, 11).

The strata between the Black Metals and the Index Limestone at the top of the group are more variable, and detailed comparisons depend very largely upon carefully-verified lithological sequences. Between Glasgow and Kilsyth the following correlations have been established:—

| *Glasgow* | *Cadder* | *Kirkintilloch* | *Kilsyth* |
|---|---|---|---|
| Upper Possil Coal | Cadder Main Coal | Meiklehill Main Coal | Haughrigg Coal |
| Upper Possil Blackband & Coal | Cadder Main Blackband & Coal | Meiklehill Wee Coal | Wee Coal |
| | Fourteen-Inch Blackband | | No. 2 Blackband |

As regards the lower seams of this part of the sequence in the Glasgow area (Possil Main Coal,[1] Lower Possil Blackband, Shale,[2] Jubilee and Gas coals) it is not certain how far they can be correlated individually with the same group of coals at Kilsyth (House, Smithy, Cloven, etc., coals). On the east side of the basin again we can correlate as follows:—

| *Bathgate* | *Wilsontown* | *Carluke* | *Auchenheath* |
|---|---|---|---|
| Smithy | Smithy | Carluke Upper | Smithy |
| Jewel | Fireclay Craw | Carluke Lower | |
| Main | Main | Tower | Dross or Lime |

[1] Known also as the Twenty-five Inch Coal locally.
[2] Known also as the Thirty Inch Coal locally.



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It would be impossible however with the information at present available to find the equivalents of these seams in the much fuller and much richer sequence present at Kilsyth (*cf.* Sections 2 and 8, Plate I).

The few correlations that can be made between Bathgate and Bo'ness across the barren tract of the Bathgate-Linlithgow Hills[1] are indicated in Plate I, Sections 5 and 6.

In the Fifeshire areas of Limestone Coal Group strata much detailed correlation work has been done in recent years. The Black Metals of the Central Coalfield are represented by a band of shales with thin clayband ribs occurring between the Glassee and Lochgelly Splint Coals (Plate I, Section 4); only in West Fife however, have marine fossils been obtained so far at this horizon (*cf.* p. 527). Here again there is a good deal of variation in the higher part of the group, both as regards number and thickness of coals, and the following table shows the nomenclature used in different areas for the principal seams, as well as the probable equivalents for these in the Bo'ness field on the south side of the Forth:—

[1] These hills are built mainly of volcanic rocks; volcanic activity in this region began in late Oil-Shale times and continued right up to Calmy Limestone times (*see* Fig. 4, p. 501).

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| *Bo'ness and Kinneil* | *West Fife* | *Central Fife* |
|---|---|---|
| Index Limestone | Index Limestone | Index Limestone |
| | Inzievar Blackband Ironstone (=Comrie No. 1 or Upper) | |
| Splint .. .. | Blairhall Main Coal .. .. | Blairhall Main Coal (*local*) |
| | *Thin Coals* .. .. | Smithy Coal (Cardenden) |
| | Success or Comrie No. 2 Blackband Ironstone | Lochgelly Blackband Ironstone |
| Seven Foot Coal .. | .. Milton Main Coal .. | *locally one seam* { Little Splint Coal / Rough or Bright Coal } |
| *Strata mainly volcanic rocks* | = { Three Foot of Blairhall / Ontake or Upper Four Foot of Comrie } | (=Fourteen Foot of Townhill) |
| | *Strata including* Comrie No. 3 or Lower Blackband Ironstone | *Strata including* Kelty Blackband Ironstone |
| | Diamond Coal of Valleyfield .. | .. Kelty Main or Fourteen Foot Coal (=Six Foot of Townhill) |
| Wester Main Coal | Five foot of Kinneddar { Jersey Upper Coal / Lower Jersey Coal .. | .. Diamond Coal / .. Swallowdrum of Cowdenbeath } Cairncubie coals of Kingseat |
| | Swallowdrum Coal .. | .. Duddie Davie of Lochgelly |
| | Ell Coal of Rosebank .. | (*not in Central Fife*) |
| *Strata mainly volcanic rocks* | Jewel Coal of Valleyfield ) | .. Lochgelly Splint Coal ) |
| | = { Splint of Kinneddar and Blarihall / Main of Oakley / Eight Foot of Rosebank } | = { Upper Eight Foot of Townhill / ? Kinglassie Splint of Kelty } Lochgelly Splint and Parrot *sometimes form one seam* |
| | | Lochgelly Parrot Coal |
| | | = { Lower Eight Foot of Townhill / ?Bank Coal of Kelty } |
| | *Blaes and Clayband ribs = Black Metals* | *Position of Black Metals* |
| | Glassee Coal .. .. | .. Glassee Coal |
| | Mynheer Coal .. .. | .. Mynheer Coal |
| Lower Ironstone .. | .. Pittencrieff Blackband Ironstone | Jewel Coal of Cowdenbeath (=Upper Five Foot of Lochgelly) |
| Six Foot Coal .. | .. Five Foot Coal .. .. | .. Five Foot Coal |
| | Two Foot Coal .. .. | .. Wee or Two Foot Coal |
| Easter Main Coal .. | .. Dunfermline Splint Coal .. | .. Dunfermline Splint Coal |
| Smithy Coal .. .. | .. .. Sulphur Coal .. .. | Stink Coal |
| Upper Carriden Limestone | Upper Kinniny Limestone | Upper Kinniny Limestone |

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For the marine band overlying the Smithy Coal of Bo'ness and the Sulphur or Stink Coal of Fife *see* p. 525.

Sections 3, 4, and 5, Plate I, show that Fifeshire cannot be closely correlated with the Central Coalfield. The Kilsyth Coking Coal for example is often underlain at a distance of 12 to 18 ft. by a 10 to 12-inch coal and the strata which include these seams are represented in Fife by the strata which include the Five Foot, Wee and Dunfermline Splint Coals. Similarly the Knott, Bannockburn Main and Steam coals of Denny and Stirling are in the same relative position in the Limestone Coal Group sequence as the Jersey Coals of Fife on the one hand and the strata which include the Cloven Coal of Kilsyth on the other. We cannot, however, correlate more closely.

The Limestone Coals of Ayrshire are shown in Plate IA, Sections 1 to 5 and 7 to 9. Where the sequence is best developed, as in the Dalry and Kilbirnie fields of North Ayrshire (Sections 8 and 9), it is possible to establish a close correlation of the coals but where marked attenuation sets in[1] we must resort to a rough correlation by means of groups of coals (Sections 1 to 4). In North Ayrshire both the Black Metals and the Johnstone Shell Bed are well-developed, although the former has so far yielded only *Lingula*. Their persistence into this region assists us to make the following correlations:—

| Glasgow District. | North Ayrshire. |
|---|---|
| Black Metals (with California Claybands). | Black Metals (with Logan's Bands) |
| Lower Blackband | Dalry Blackband |
| Garibaldi Claybands | Garibaldi Claybands |
| Kilsyth Coking Coal | Coal, a few inches |
| Johnstone Shell Bed | Johnstone Shell Bed |
| Johnstone Clayband | Dalry Clayband |

In the more variable strata above the Black Metals however, only tentative group-correspondences can be given (Plate IA, Sections 9 and 10).

The Black Metals and Johnstone Shell Bed are again readily

[1] *See* p. 450.

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recognisable in the Coalburn (Sheet 23) and Muirkirk (Sheet 15) sequences (Sections 5 and 6) but cannot be identified in Central or South Ayrshire (Sections 1 to 3). We cannot correlate the Limestone coals of North Ayrshire with those at Patna and Dailly for example, and even in the latter fields, owing to variations in sedimentation and to splitting of the coals, only tentative group correlations can be given.

The Limestone Coal Group sequence of coals as developed at different localities in Midlothian and in East Lothian is illustrated in Plate II. It will be seen that even in the case of such a well-defined geological unit as the Midlothian Basin there is difficulty in establishing correlation throughout. The main criteria made use of are lithological sequences, although there are a few fossiliferous horizons which help to link one section with another. No equivalent for the Black Metals of the Central Coalfield has yet been recognised; in the Newtongrange field, however, an impure limestone or calcareous sandstone, 2 to 3 ft. thick and containing abundant *Productus semireticulatus*, has been obtained from the centre of a 30-ft. band of shales lying a little way below the Coronation Coal. This bed, which occurs near the centre of the Limestone Coal Group, may perhaps represent the marine band found in the Black Metals of the Central Coalfield. The *Lingula*-shale overlying the Blue or North coal at Niddrie probably corresponds with the *Lingula* band so constantly present on the east side of the basin in the roof of the Arniston Parrot (Arniston, Newtongrange, Tranent). A marine band found in a recent boring at Tranent between the Hauchielin (or Arniston Parrot) and No. 2 Diamond coals would appear to correspond to the marine band found between the Smithy and Easter Main coals at Bo'ness (*cf.* p. 526). Scattered *Lingula* shells have also been obtained at two or three other horizons, i.e. above the Kailblades Coal at Arniston, associated with abundant fish-remains in the roof of No. 1 Ironstone at Loanhead, and between the Blackchapel and Little Splint Coals at Niddrie.

It will be seen from Plate II that while we can correlate more or less closely the main coals on the west side of the basin (Niddrie to Penicuik), and similarly those on the east side (Arniston to Dolphingston), reliable correlations can not be established from one side to the other. The North or Blue Coal of the west however, appears to be the equivalent of the Arniston Parrot or Hauchielin of the east, while the Corby Craig Coal is on approximately the same horizon as the Kailblades.

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*Acknowledgements*:—In the preparation of the paper I have drawn freely on the work of present and former colleagues on the Geological Survey and to all of these I wish to tender my sincere thanks. To Mr. J. Pringle especially my thanks are due for reading through the palaeontological portions and giving me the benefit of his expert knowledge. The coloured geological map and the Sheets of comparative vertical sections forming Plates I, II and III, originally prepared to accompany this paper, have since been published in ' A Survey of Scottish Coking and Furnace Coals.'[1] For permission to reproduce these and for the use of the blocks acknowledgement is due to the Controller of H.M. Stationery Office.

I should like to add, in conclusion, that the present paper is merely, as its sub-title indicates, an *Introduction* to the study of the Scottish Carboniferous sediments. A number of important aspects have only been briefly touched upon. Nevertheless the paper may be of some use to students of geology and mining until a more complete and authoritative account is forthcoming.

## EXPLANATION OF PLATES.

Coloured Map showing distribution of Coal Measures, Millstone Grit, and Carboniferous Limestone Series. The older rocks (Calciferous Sandstone Series, Old Red Sandstone, etc.) left white. The New Red Sandstone (? Permian) of Central Ayrshire is also uncoloured.

Plate I. Comparative Vertical Sections, Limestone Coal Group. The Top Hosie Limestone is now correlated with the Upper Kinniny (No. 1 Carriden) Limestone, the Johnstone Shell Bed with the marine band above the Sulphur (Bo'ness Smithy) Coal. The correlation lines at the foot of Sections 4 and 5 require to be altered accordingly.

Plate IA. Comparative Vertical Sections, Limestone Coal Group (continued). Sections 1 to 3, One-inch Sheet 14; Section 4 and 5, Sheet 15; Section 6, Sheet 23; Sections 7 to 9, Sheet 22.

Plate II. Comparative Vertical Sections, Limestone Coal Group (continued). Midlothian and East Lothian.

Plate III. Comparative Vertical Sections, Productive Coal Measures.

Plate IV. Comparative Vertical Sections, Lower Carboniferous Rocks of Scotland and North of England. *Facing page* 471.

[1] Department of Scientific and Industrial Research Board; Fuel Research Board; Survey Paper No. 15, 1930.

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No. XVIII.—Radioactivity and Earth Movements. By Arthur Holmes, Professor of Geology, The University, Durham.


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## I.—TECTONIC HYPOTHESES.

Both external and internal geological processes are controlled by gravity and the earth's bodily movements. The circulations of matter which constitute the external processes are maintained by energy derived from the sun, whereas the internal processes derive much of their energy from the earth's internal heat, the latter being partly an inheritance, and partly an income supplied by atomic disintegration. Hypotheses relating to the physical causes of earth movements must take all the relevant factors into consideration as fully as the data permit. At present there is a plethora of hypotheses in the field, some of which are mutually contradictory. Much of this confusion is a result of lack of data, and is temporarily unavoidable; on the other hand a good deal is unnecessary, and has been introduced by exaggerating the effects of certain factors while ignoring those of others. The most remarkable example of a neglected source of geological



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energy is the heat generated by the radioactive elements. Outside the British Isles there has been little recognition of the importance of this factor, and it is therefore hardly a matter for surprise that hypotheses in which it is ignored should prove to be inadequate.

Among the forces to which appeal has been made are the following (21):—

*Gravitational*:

*Cosmic* Stresses set up by

(*a*) Tides due to the sun and moon.

(*b*) Precession of the equinoxes.

*Terrestrial*

(*c*) Attraction between continents.

(*d*) *Pohlflucht* force.

Stresses set up by

(*e*) Departures from isostatic equilibrium.

(*f*) Departures from hydrostatic pressure in the crust.

(*g*) Condensation due to re-adjustments of the material of the earth.

*Thermal*:

Stresses set up by

(*h*) Contraction due to change of state and cooling by conduction.

(*i*) Expansion due to heating-up of the earth's interior.

(*j*) Contraction (*h*) and expansion (*i*) alternating in time (Joly's hypothesis of thermal cycles).

(*k*) Convection currents in the substratum (the hypothesis developed in this paper).

(*a*) Tidal stresses, due mainly to the frictional drag of shallow seas against the crust, retard the earth's rotation. This involves a bodily contraction of the earth and an approach towards a spherical form (65, p. 293). Schaffer has recently developed the geological consequences (91). Lee, however, adopts the opposite view that, despite this effect, the earth's rotation has been periodically accelerated as a result of gravitational condensation (79). Taylor appeals to tidal forces as the chief cause of Tertiary mountain building and continental drift. He requires, however, that the earth should have captured the moon towards the close of Cretaceous time (99, p. 158). Wegener regards a westerly drift of the continents, due to bodily tidal friction, as a possible

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factor in his far-reaching hypothesis of continental drift (108). As shown by Jeffreys (65, p. 322) and Lambert (75) the actual force is negligible. It would have to be ten thousand million times as powerful as it now is to produce the effects ascribed to it, and moreover, if it were, it would stop the earth's rotation altogether in about a year. We may therefore conclude that *the dominant forces involved in crustal movements must arise within the earth itself.* Joly requires a westerly tidal drift of the whole crust over the substratum (66) and this again is considered by Jeffreys to be inadequate to produce the required effects in the time available (61).

(*b*) Precessional forces have been referred to by Wegener and others, but they are clearly of little importance (59).

(*c*) See 59, p. 418.

(*d*) The *pohlflucht* force tends to move the continents towards the equator. It is a differential gravitational force resulting from the ellipticity of the earth. Jeffreys finds that its maximum value, in middle latitudes, is about 5,000 dynes per sq. cm. (59). This force has been appealed to as a cause for continental drift, but it is hopelessly inadequate at the present day, and with the present viscosity of the substratum it is equally incapable of moving the crust over the interior in any reasonable time (59).

But in the early stages of the earth's history, for example when the moon separated, the viscosity must have been very much lower and the crust should then have reached the stable position determined by a symmetrical distribution of the continents about the equator. Since the continents are not so distributed at the present day, *some other force must have operated in opposition to the* pohlflucht *to move them into the positions they now occupy.*

(*e*) Departures from isostasy, brought about by denudation and deposition and the resulting underlying thermal changes, are thought by Bowie to provide horizontal stresses adequate to account for the folding and overthrust structures of mountain systems (12). This hypothesis is both inadequate and internally inconsistent. Staub appeals to isostasy to generate currents in the substratum directed away from the roots of mountain systems previously compressed by approaching continents. The currents then drag the continents apart again, leaving a geosyncline between (96). This is like trying to lift oneself by one's own boot laces.

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(*f*) Gutenberg has recently advocated deviations of the earth's crust from hydrostatic pressure as an important source of tectonic energy (37). Jeffreys requires rock-flowage in the crust to account for the fact that mountain ranges have been lowered and even submerged before the cover of sedimentary rocks had been removed by denudation. He suggests that the excess of pressure due to the weight of the mountains leads to plastic outflow of matter from the intermediate layer (see p. 568) with a compensating inflow in the lower layer (65, p. 295). The development of bordering geosynclines such as the Indo-Gangetic "trough" is inconsistent with this hypothesis. Daly has suggested for discussion a hypothesis of continental creep due to the sliding of sial blocks on a lubricating zone of glassy basalt (23). A bulging of the polar and equatorial regions with a depression between, towards which the continents migrate, is pre-supposed. No explanation is offered for the initiation of so unstable a deformation of the globe.

(*g*) The effects of gravitational condensation in a heterogeneous earth were fully explored by T. C. Chamberlin (18), but these are of interest only to those who accept the Planetesimal hypothesis. A discussion of the tectonic consequences, with experimental illustrations of general interest, has been provided by R. T. Chamberlin (17). Keith considers that the chief cause of orogenesis is to be found in the thrust against the continents due to the downward pull of gravity on the floors of adjacent oceans, combined with batholithic intrusion actuated by the resulting pressure on reservoirs of magma already in the crust (71 and 72).

Differential rock flowage is involved in many of the hypotheses mentioned, and this is made the fundamental consideration in a hypothesis of mountain building developed by Andrews (7). In this case, however, the flowage is not from ocean to continent, but results in a dynamic progression of folded belts from the interiors of the continents outwards. It is not clear to what forces the rock flowage is to be attributed. Convection currents in the substratum would adequately provide the necessary mechanism. As early as 1875, Suess deduced from his Alpine studies that "a mass movement, more or less horizontal and progressive, should be the cause underlying the formation of our mountain systems." His conception of the process was inevitably cloudy, but he accepted earth shrinkage, referred in part to the cooling of the crust, as a factor of prime importance.

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This introduces us to the suite of hypotheses in which thermal processes play the leading part. The earlier attempts, antedating the discovery of radioactivity, need not be discussed. Those developed since are of four chief kinds; they may all be tested by comparing their consequences with the geological behaviour of the earth's crust.

(*h*) In 1915 I adopted the traditional hypothesis of a steadily cooling earth, and assumed that the effects of radioactivity were limited to slowing down the rate of cooling. Instead of calculating the age of the earth from the present thermal state of the crust, as Kelvin had done, I took the age as a known datum and assumed that radioactivity fell away exponentially with depth, so that the present average gradient could be reached after 1,600 million years of cooling. With a known distribution of radioactivity, it was then possible to calculate the present downward variation of temperature (44 and 45). The work has since been repeated by Jeffreys (65) and Adams (1).

The consequences of this hypothesis (which reconciles all the more obvious thermal data quite satisfactorily) have been very thoroughly explored by Jeffreys (65). In 1925, however, I abandoned the hypothesis because of its failure to account for the leading phenomena of geological history (47). The objections are:

(1) Its inconsistency with the prevalence of vulcanism of the plateau-basalt type. Jeffreys now suggests that the necessary rise of temperature in his basaltic layer may be due to the reaction of chemically active gases derived from the underlying layers (65, p. 298). This is a quite unacceptable extension of Day's brilliant work on volcanic activity (24).

(2) Its quantitative inadequacy to provide the contraction necessary to produce folded and overthrust mountain structures. The calculated reduction of area is only about one sixth of the amount calling for explanation (50).

(3) The distribution of orogenic periods in time is systematically different from that deduced from the hypothesis (50). By admitting deep-seated cooling by convection, Jeffreys now provides more nearly uniform intervals between successive orogenic periods (65, p. 292), but only at the expense of discrepancy (2) which becomes still greater.

(4) The improbability that compression dispersed through

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a layer 150 km. thick could produce relatively superficial nappe structures like those of the Alps.

(5) The failure of the hypothesis to account for marine transgressions, and particularly for the development of geosynclines (50).

(6) The fact that under the hypothesis continental drift is manifestly impossible. It is of no service to say, as Jeffreys does (65, p. 305), that continental drift is "out of the question." See p. 584.

(7) No geochemical reasons are offered for the fundamental supposition that the substratum is so poor in the radioactive elements that its heat output can be ignored.

(*i*) In the remaining hypotheses this unnatural limitation of radioactivity to the crust is rejected. The geochemical and physical evidence, as we shall see, is certainly in favour of a slightly radioactive substratum and this implies the production of an excess of heat over and above that conducted to the surface. In flat contradiction to the contraction hypothesis, Lindemann considers the earth to be expanding as a result of the continuous internal accumulation of radio-thermal energy (80 and 87). However, this idea is geologically untenable. Many processes would intervene to permit the escape of excess heat and cumulative expansion would not occur so long as these continued to operate. Moreover, if the earth began as a fluid body it is obvious that it must have contracted from its initial volume until it reached a state of approximate or fluctuating equilibrium, in which case one of the two following hypotheses would apply.

(*j*) In Joly's well-known hypothesis of thermal cycles an alternating accumulation and discharge of heat is visualised (66). Accumulation leads to fusion of the substratum (regarded as of basaltic composition); crustal extension; volcanic activity; and marine transgressions. Westerly tidal drift of the crust slowly draws the ocean floors over the magma zone, and discharge of heat is brought about by thinning of the oceanic crust. Solidification sets in by crystallisation and the sinking of blocks, accompanied by crustal compression and marine recessions.

As the period of Joly's cycles seemed to be inconsistent with the duration of geological time as estimated from lead-ratios, I suggested in 1925 the possibility of longer periods referred to similar cycles arising in a substratum of peridotitic composition,

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the radioactivity of which was regarded as being much less than that of the " basaltic " layer above it (48). This conception has been further developed by Krige with special reference to the currents which would be set up between the hotter sub-continental and the cooler sub-oceanic regions (74). These modifications of Joly's original scheme do not, however, remove the physical difficulties in the way of its acceptance.

Jeffreys has vigorously assailed the hypothesis of thermal cycles on the grounds that alternation of the fluid and crystalline states could not occur, since the substratum would remain permanently fluid on the postulated conditions; and that tidal drift of the crust over the substratum could not occur at the required rate (61). MacCarthy has pointed out that rapid loss of heat through the ocean floors would involve abnormal heating of ocean water (83). Lotze has attacked both Joly's scheme and my proposed modifications by confronting them with the complexities of earth history (81 and 82). It must be admitted that there is no evidence of world-wide compression alternating in time with world-wide tension. Compression of the crust, even in subsiding areas of long-continued sedimentation, seems always to have been in progress somewhere or other. Tensional phenomena, when they occur, are contemporaneous with compressional phenomena elsewhere. Thus the sudden opening of the Uralian geosyncline took place at the close of the Silurian while the Caledonian belt was being strongly folded.

Though his mechanism for bringing about the loss of excess heat is unsatisfactory, Joly has boldly faced the situation that arises if an excess of heat is generated in the substratum, and he has clearly realised that some form of crustal drift is absolutely necessary to permit the discharge of such heat.

(*k*) From the above discussion it will be realised that the substratum should still be in a " fluid " or glassy state. One of the objects of this paper is to discuss a mechanism for discharging the excess heat, involving circulation of the material of the substratum by convection currents, and continental drift operated by such currents. Tidal friction may co-operate to a slight extent, but is not essential. The possibility that currents might be set up by differential radioactive heating was recognised by Bull in 1921 (14), though in 1927 he considered that little evidence could be adduced in its support (15, p. 155). Ampferer has postulated *unterströmungen* in the substratum to explain crustal

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movements (5), and Schwinner considers the currents to be due to convection (94). Kraus also finds it necessary to adopt magmatic currents to explain the evolution of geosynclines, orogenic belts and continents (73). Born has pointed out that, although such hypotheses thoroughly meet the geological requirements, they suffer from the defects that they demand extensive movements in the substratum and require a source of energy that has not been made intelligible (38, p. 124). But one need not look far for an adequate source of energy. It is to be found in the radioactive elements. To the distribution of these we now turn, first considering the nature of the substratum and the overlying crust.

## II.—THE NATURE OF THE CRUST AND SUBSTRATUM.

In recent years the comparative study of the seismograms of near earthquakes has thrown new light on the structure of the continental crust. The recognition of the Pg, P* and P waves and the corresponding S waves indicates that three distinct layers, known respectively as upper, intermediate and lower, are concerned in their propagation (65, Chap. VI). The velocities of waves of the P and S types are given by the formulæ

$$Vp = \frac{13.13}{\sqrt{10^6 \beta d}} \text{ and } Vs = \frac{7.37}{\sqrt{10^6 \beta d}}$$

where $\beta$ is the compressibility and d is the density of the material through which the waves are propagated. Thus, we have

$$\beta d \times 10^6 = 96.8/Vp.Vs$$

which can be calculated for each of the layers. Adams and Williamson (4) and Adams and Gibson (2 and 3) have determined $\beta$ for a representative series of rocks and minerals at various pressures up to 12,000 megabars. From the data for minerals the compressibility of a rock can be calculated by adding together the products of volume percentage of each mineral by its compressibility. Some representative results are compiled in the following tables.

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| Layer | Vp | Vs | $\beta d \times 10^6$ |
|---|---|---|---|
| Upper .. .. | 5.4—5.6 | 3.2—3.3 | 5.60—5.24 |
| Intermediate .. | 6.3 | 3.7 | 4.15 |
| (Top of) Lower .. | 7.7—7.8 | 4.25—4.35 | 2.95—2.85 |

See Jeffreys (62); Gutenberg (38); and Terada and Miyabe (100).

| Rock | Pressure (megabars) | d | $\beta \times 10^6$ | $\beta d \times 10^6$ |
|---|---|---|---|---|
| Granite .. .. | 2,000 | 2.61 | 2.11 | 5.51 |
| Granodiorite .. | ,, | 2.69 | 1.82 | 4.90 |
| Diorite .. .. | ,, | 2.74 | 1.61 | 4.41 |
| Diorite .. .. | 7,000 | 2.76 | 1.53 | 4.22 |
| Tachylyte .. | ,, | 2.87 | 1.45 | 4.16 |
| Amphibolite .. | ,, | 2.90 | 1.30 | 3.77 |
| Gabbro .. .. | ,, | 3.06 | 1.16 | 3.55 |
| Peridotite .. | 10,000 | 3.44 | 0.91 | 3.13 |
| Dunite .. .. | ,, | 3.32 | 0.79 | 2.62 |
| Eclogite .. .. | ,, | 3.50 | 0.80 | 2.80 |

The *Upper Layer* has been generally identified with granite, but petrological evidence indicates that the range of rocks of the sial suite is from granite to diorite, and that granodiorite is nearer the average composition than granite. Moreover, the properties of the layer are complicated by the presence of a sedimentary and schistose cover of very variable thickness, and by widely distributed intrusions of basic rocks. The observed value of $\beta d$ is higher than that calculated from the data for the rocks known to be present, and this difference must not be overlooked in the attempt to identify the materials of the underlying layers. Another point of importance is that the deeper parts of the upper layer, wherever exposed to observation, are found to exhibit structures due to flowage, the characteristic types being gneisses and amphibolites. It is therefore to be anticipated that the intermediate layer will also be characterised by fluxion structures.

The thickness of the upper layer is found by Jeffreys to be about 10 km. in the neighbourhood of Great Britain and the

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adjoining parts of Europe, rising to 12 km. when the Alpine region is included (62). Gutenberg (38) and the Japanese seismologists find rather higher values (86).

The *Intermediate Layer* has given rise to much discussion. Jeffreys cautiously favours an identification with tachylyte (glassy basalt), but this is unacceptable on geological grounds. I suggested diorite or quartz-diorite as a more reasonable alternative (52). Wagner has recently attacked the problem in the light of the evidence provided by the xenoliths of the South African kimberlite pipes (104). He concludes that the upper layer is underlain by a shell composed predominantly of amphibolites accompanied by gabbros and basic granulites. The $\beta$d value for amphibolite, $3.77 \times 10^{-6}$, is a little lower than that found from seismic evidence, $4.15 \times 10^{-6}$, but, as we have seen, this difference is favourable to the identification rather than otherwise. If, as seems probable from the diamond-pipe evidence, the amphibolite layer passes down into granulite, the intermediate layer should provide seismic evidence of a double character. Mr. R. Stoneley has informed me that he has recently detected a hitherto unrecognised wave between P* and P. This discovery is consistent with the existence of a granulite layer, and affords a remarkable confirmation of Wagner's reading of the geological evidence.

Diorites and quartz-diorites are likely to be

(*a*) differentiation products of granodioritic magmas;

(*b*) products of reaction between granitic magmas and sediments in the hearts of mountain systems; or

(*c*) hybrid rocks due to interaction between basaltic magmas and granitic rocks or magmas.

They are essentially sialic rocks, and if we admit their presence in the upper layer, as we must, there is no longer any reason to postulate their abundance in the intermediate layer. As a working hypothesis the latter will here be regarded as amphibolite, probably passing downwards into granulite, both facies being subject to local transformation into eclogite under appropriate dynamic conditions (25).

The thickness of the intermediate layer is found by Jeffreys to range from 20 to 25 km. Other observers confirm these figures or favour a slightly greater thickness.

The *Lower Layer* may be eclogite or some form of peridotite, identifications that are supported by Wagner's discussion of the

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kimberlite xenoliths. Geochemical and petrological evidence and the analogy with meteorites suggest that the lower layer is most likely to be of peridotitic composition, while the thermal evidence favours the view that the material is in a glassy rather than a crystalline state. Unfortunately the values of $\beta$d for glassy peridotite under different pressures have not yet been determined. Such material would be very difficult to prepare in blocks suitable for investigation. It is probable, however, that at high pressures the relatively higher values of $\beta$ and lower values of d characteristic of glassy materials will closely approach those of the equivalent crystalline materials. If the crust passes down into a glassy substratum the temperature of the lower surface of the crust will be that of the melting point of the material occurring there. Thus it is probable that the top of the lower layer may be crystalline. Seismic evidence would give no indication of the change unless the downward variation of $\beta$d became discontinuous in the zone of change of state. The known variation of $\beta$d is a continuous increase to a depth of 2,900 km., the increase being in accordance with the change of pressure and not necessarily requiring any further change of composition. It should be noticed that the seismic evidence does not prove, as is commonly assumed, that the lower layer is crystalline, but only that it is highly rigid. It is also highly viscous and is therefore mechanically indistinguishable from a solid. It may nevertheless be " fluid " in the sense of lacking strength and crystalline structure.

The term *crust* is used for the upper and intermediate layers and any part of the lower layer that is crystalline, while the term *substratum* is adopted for the underlying thermally " fluid " or glassy part of the lower layer.

As pointed out over half a century ago by F. J. Evans (28, p. 27) the variations of the earth's magnetism suggest a change of state in passing from the crust to the substratum. More recently Chapman has drawn attention to this neglected source of information about the earth's interior. He states that at a depth of some 300 km. the value of the electrical resistivity is about $3 \times 10^{12}$ e.m. units, whereas for the crystalline rocks of the crust the value is $10^{15}$—$10^{16}$ and rises with temperature (19). Not only does the great difference indicate a change of state, but, as Chapman remarks, " despite the mechanical stability of the earth, fairly rapid changes are proceeding within

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it," suggesting that " the interior is much more mobile than the outer layers."

Turning now to the oceanic part of the crust, we have little information except that its properties are consistent with its identification as gabbro or amphibolite (65, p. 115). For the Pacific floor the group-velocity of Love waves with a period of about 20 secs. is 3.8 km./sec. or more, as compared with 3.2 km./sec. for the Eurasian crust. The respective velocities of Sg (which should be about the same as these particular group-velocities) are 3.8 and 3.9 for amphibolite and gabbro, and 3.1 and 3.3 for granite and granodiorite. Other seismic evidence (41), as well as petrological and isostatic considerations, supports this identification, and we may therefore regard the Pacific crust as being like that of the continents, but with gabbro passing down into amphibolite in place of the sialic upper layer. In the floor of the Atlantic, and to a less extent in that of the Indian Ocean, there appear to be patches of sial lying above the " gabbro-amphibolite " layer. The thickness of the oceanic crust is probably of the same order as that of the continents; thermal considerations suggest that the former is likely to be thicker than the latter. The lower layer of the oceanic areas cannot be distinguished from that lying beneath the continents. The substratum thus appears to be a continuous shell bounded above by the crust and below by the metallic core. The core extends from 2,900 km. to the centre and its nature is reasonably well established by many converging lines of evidence.

## III.—THE RADIO-THERMAL ENERGY GENERATED IN ROCKS.

Since Kelvin's method of dealing with the problem of the earth's thermal history was shown to be invalid by Lord Rayleigh's discovery of the widespread distribution of the radio-active elements in rocks (98), various attempts have been made to tackle the problem afresh. Although numerically the actual proportions of the radio-elements (other than potassium) are exceedingly small, yet owing to the fact that their disintegration is accompanied by the liberation of heat, their presence is of an importance that cannot be overemphasized. The total annual heat outputs are as follow (56):

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| | |
|---|---|
| Uranium family .. .. | 7,900 x 10-$^{4}$ cals./gm. U. |
| Thorium family .. .. | 2,300 x 10-$^{4}$ cals./gm. Th. |
| Potassium .. .. .. | 1.24 x 10-$^{4}$ cals./gm. K. |
| Rubidium .. .. .. | 2.38 x 10-$^{4}$ cals./gm. Rb. |

The geothermal effects of potassium are of the same order as those of the more strongly radioactive families, because of the great abundance of potassium in rocks. The output from rubidium, however, can be ignored because of the rarity of this element.

In the following table the average contents of the radioactive elements in rocks have been compiled, and from these data and the heat outputs cited above, the total generation of heat in average rock-types is calculated.

*Heat Production per annum in Rocks, etc.*

| Types of Material | U x $10^{6}$ | Th x $10^{6}$ | K x $10^{2}$ | Total Heat Production (Calories per annum) | |
|---|---|---|---|---|---|
| | | | | per $10^{6}$ gm. | per $10^{6}$ cc. |
| Granites .. | 9.0 | 20.0 | 3.4 | 15.9 | 42.2 |
| Granodiorites .. | 7.7 | 18.0 | 2.5 | 13.3 | 36.4 |
| Diorites .. | 4.0 | 6.0 | 1.7 | 6.7 | 19.0 |
| Central Basalts: | | | | | |
| Continental . | 3.5 | 9.1 | 1.9 | 7.2 | 20.9 |
| Oceanic .. | 3.6 | 7.1 | 1.8 | 6.7 | 19.5 |
| Plateau Basalts | 2.2 | 5.0 | 0.8 | 3.9 | 11.4 |
| Gabbros .. | 2.4 | 5.1 | 0.7 | 3.9 | 11.7 |
| Eclogites .. | 1.0 | 1.8 | 0.4 | 1.7 | 5.8 |
| Peridotites .. | 1.5 | 3.3 | 0.8 | 2.9 | 9.4 |
| Dunites .. | 1.4 | 3.4 | 0.03 | 1.9 | 6.6 |
| Meteorites: | | | | | |
| Stony .. | 1.7 | 0.9* | 0.16 | 1.8 | 5.8 |
| Stone-iron .. | 1.0 | n.d. | — | — | — |
| Iron .. .. | 0.07 | n.d. | n.d. | — | — |

* This is a single determination by Joly (*Phil. Mag.* (6), 18, 1909, page 142) and may not be representative.

It is important to make sure that practically all the energy liberated by atomic disintegration does, in fact, appear as heat, for Evans has suggested that " it is probable that a considerable proportion of the energy liberated . . . . . is used up in effecting physical, chemical or atomic changes in the surrounding minerals " (27, p. lx). If this view were correct, we should expect the heat generated by radium in a glass container and determined experimentally, to be much less than the heat equivalent calculated

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from the energies of the rays emitted. Yet, despite the intense colouration of the glass, the calculated and observed heat outputs agree almost exactly. The total heat from one gram of radium and its short-lived daughter elements was observed by Meyer and Hess to be 137 cals./hour. The calculated output is 137.14. We may therefore safely conclude with Rayleigh (70, p. 55) and Lawson (78) that the evidence decides conclusively against the suggestion of Evans.

It is also important to know whether there is any possibility of inhibition of heat output when the radio-elements are deeply buried in the earth. All experimental work directed to test this, involving temperatures up to 2,500°C., very high pressures, and bombardment by every kind of ray, has failed to affect the progress of disintegration in any appreciable way. The quantum theory provides the explanation. To disturb the interior of the atomic nucleus—the seat of the instability that leads to decay—temperatures of the order 3,000 million degrees and correspondingly high pressures would be theoretically necessary. There is clearly no reason to suppose that any of the conditions obtaining within the earth could influence the rates of atomic disintegration.

It follows that to ignore the ceaseless outpouring of energy that is everywhere occuring in terrestrial materials would be as wrong as to ignore the effects of gravitation.

## IV.—THE DECREASE OF RADIOACTIVITY WITH DEPTH.

We must next compare the heat-output of the rocks with that lost from the continents by conduction to the surface and radiation into space. The average amount of heat so lost from each sq. cm. per second is given by the product of the average thermal conductivity of rocks (0.006) and the average temperature gradient (0.00032° C. per cm.). The loss per year ($3.15 \times 10^7$ secs.) is therefore

$$0.006 \times 0.00032 \times 3.15 \times 10^7 = 60 \text{ calories/sq. cm.}$$

Evidently this could be made good by the radio-thermal energy generated within a thickness of 14 km. of granite; 16.5 km. of granodiorite; 52 km. of plateau basalt or gabbro; or 60 km. of peridotite. It may therefore be inferred that the earth's radioactivity is strongly concentrated towards the surface.

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The facts of distribution and the geochemical behaviour of the elements in question are definitely in accord with this inference (43, 49, 89). However we may combine the thermal data on p. 571 with the seismic and petrological evidence bearing on the structure of the crust it seems certain that an outer shell of the earth less than 60 km. thick must generate sufficient heat to make good the loss from the surface. The distribution of radioactivity favoured by Jeffreys, and limited to allow the interior of the earth to cool, corresponds with a layer of granite 11 km. thick underlain by a basaltic layer 22 km. thick. There is then no excess of radioactivity left over for the interior. The temperatures of the basaltic layer are about 300° C. at the top and 650° C. at the base (65, p. 297). Clearly these are too low to permit vulcanism of the plateau-basalt type. If basalt magma comes from a greater depth, the distribution of radioactivity necessarily involves the production of an excess of heat, and igneous activity becomes the mechanism by which part of the excess is enabled to escape. But in this case the original restrictions imposed by the hypothesis of limited radioactivity have been fatally exceeded. The substratum becomes permanently "fluid" in the thermal sense and the earth cannot cool down in the manner postulated (47).

Jeffreys has shown that if the limited amounts of the radio-elements admitted to be present in the crust were uniformly distributed through the 2,900 km. shell, then the material below a depth of some 50 km. could never have solidified. Convection would then proceed in the substratum until the radio-elements became strongly concentrated towards the surface. He writes, "the transfer would only stop when the temperature gradient at all depths had become so low as to permit solidification. This implies that the concentration would ultimately be almost complete" (65, p. 146). I can see no reason for supposing that the freeing of the substratum from the radio-elements can yet have become as complete as Jeffreys requires. All the experience of geochemistry is strongly opposed to such a hypothetical possibility. No process of magmatic differentiation is known that could bring it about. It is likely that the material of the upper layer, together with the oceans and the atmosphere, was differentiated from the general body of the earth while the latter was still a relatively mobile fluid. The process of "gaseous transfer" so implied would be very effective in leading to a marked

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concentration of the radio-elements in the first-formed crust. But the known radioactivity of basalts and peridotites of widely different ages shows that the suggested process was far from removing all the radio-elements from the substratum. Yet clearly, if we admit only a slight radioactivity in the substratum there must be generated within it an excess of heat which would maintain fluidity.

Let us suppose, to illustrate the effects of slight radioactivity, that the heat output within the substratum is only 1/700 of that of plateau basalt. On geochemical grounds it is difficult to see how this can be anything but an underestimate. The volume of the substratum (60 km. to 2,900 km.) is $88.75 \times 10^{10}$ cu. km., and the total heat generated per year on the assumed figure is $142.5 \times 10^{17}$ calories. This is equivalent to the cooling of 62 cu. km. of basaltic magma from 1,000° C. to a crystalline rock at 300° C. Obviously, to get rid of this quantity of heat some process much more drastic than ordinary volcanic activity would be called for. The volume of lava in the 1929 eruption of Vesuvius was only $12 \times 10^{-3}$ cu. km. The annual loss of heat from all volcanic sources has been estimated at $6 \times 10^{17}$ calories (82, p. 83).

For the accumulated heat of 200 million years to escape through the sites of the oceans it would be necessary for one third of the whole of the ocean floors (taken at 60 km. thick) to be engulfed and heated up to 1,000° C., and replaced by magma which cooled down to form new ocean floors at 300° C. A process competent to bring about this result on the scale indicated would be some form of continental drift involving the sinking of old ocean floors in front of the advancing continents and the formation of new ocean floors behind them.

We may therefore conclude that

(*a*) if the crust of the earth makes good the loss of heat by conduction to the surface, and

(*b*) if the substratum has only 1/700 of the heat-generating capacity of plateau basalt; then

(*c*) the substratum cannot yet have cooled sufficiently to have crystallised, but must still be in the stage of convective circulation, and

(*d*) to avoid permanent heating-up, some process such as continental drift is necessary to make possible the discharge of heat.

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## V.—CONVECTION CURRENTS IN THE SUBSTRATUM.

### The Conditions for Convective Circulation.

In the simple case of an extensive layer of uniformly heated viscous liquid, with rigid conducting surfaces above and below, the conditions leading to convection currents are fairly well understood. There is stability until a certain critical temperature gradient is reached, depending upon the compressibility, conductivity, and viscosity of the fluid. As the critical gradient is exceeded, the uniformly stratified distribution of material becomes unstable, and in the attempt to restore stability a system of complementary currents begins to develop, ascending in some places and descending in others. The disturbances are at first chaotic, but of all the possible systems of movement some tend to persist and to increase steadily with time at the expense of others. This leads gradually to the survival of local centres from which vertical currents ascend. Towards the top the currents spread out in all directions from each centre until they interfere with one another, turn downwards, and form sheet-like return currents. Thus irregular polyonal prisms come to be enclosed by the downward currents. Under ideally uniform conditions the polygons would ultimately become hexagonal and the diameter of the hexagons would be three or four times the depth of the convective layer (60).

In the earth the critical gradient appears to be about 3° C. per km. So long as this is exceeded convection must go on, provided that the material has no strength, and that the viscosity is not too high.

Jeffreys has shown that the viscosity of the substratum cannot by itself prevent convection (63). To stop convection in a layer nearly 2,900 km. thick, the viscosity would need to be of the order $10^{26}$ c.g.s. From the 14 monthly variation of latitude the mean viscosity is found to exceed $5 \times 10^{20}$ (59, p. 424). The actual value is certainly not much higher than this. Since the beginning of the last withdrawal of the European and North American ice-sheets, the time T elapsed is nearly 20,000 years, or $6 \times 10^{11}$ secs. Important upward movements, referred to the relief of load consequent upon the melting of the ice, have occurred over areas of a linear extent L of the order 1,000 km. or $10^8$ cm. The thickness H of the substratum involved in the isostatic adjustments is between 30 and 3,000 km. ($3 \times 10^6$ and $3 \times 10^8$



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cm.). The relation between these factors and the viscosity V is given by $3\ VL^2 = g\ H^3T$, g being nearly 1,000. With these data we find V lies between $5 \times 10^{17}$ and $5 \times 10^{23}$. Even the maximum value is well below the limiting value $10^{26}$.

At high temperatures the strength of materials rapidly diminishes and, as the fusion point is approached, it disappears. It is therefore to be expected that the substratum should be devoid of strength. Geologically, the abundant evidence pointing to regional isostatic compensation within a depth of 60 km. or less is the best indication that this expectation is realised. Jeffreys, however, infers from the fact that the equator of the geoid is not exactly circular that deep-seated stress-differences must be resisted by the substratum, and that the latter must therefore have at least a little strength (65, p. 222). The viscosity would then be infinite until this was overcome. The bulge of the equator corresponds to an excess of material about the longitude of Central Africa. Such an upward bulge of Africa is undoubtedly genuine, but it has developed since the Cretaceous from a state of almost perfect peneplanation (55 and 107). Thus Central Africa has been affected—and still is—by a process which has actively uplifted the region faster than isostasy could restore equilibrium. It is well-known that isostasy is most disturbed where recent movements have been most active; perfect adjustment implies relatively static conditions. So far from proving the existence of deep-seated strength, the development of the bulge proves that some dynamic process is operating in the substratum sufficiently actively to maintain a slight departure in advance of complete compensation.

In further support of the inference that the substratum has no strength we can appeal to the secular variation of the earth's magnetism, which, as already pointed out, implies relative mobility of the interior. The only theory which provides for the maintenance of the earth's magnetism, and which is not contradicted by other observed facts, has been proposed by Larmor (76); it involves the circulation of the material within the earth by a system of currents symmetrical about the axis and the magnetic equator (19).

Granting the physical possibility of convection within the substratum, the effect of radioactivity would be to steepen the gradient over the critical gradient and so increase the rate of circulation until the new heat could be carried off as fast as

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it was generated. With the differentiation and crystallisation of the crustal materials, the interior would be able to discharge the excess heat only in so far as the crust could be fused or broken through from below. Both processes are described in the sections that follow.

The mode of circulation of the material of the substratum can be deduced from general principles. It will depend mainly

(*a*) on the varying thickness of the substratum from equator to poles;

(*b*) on the varying thickness and radioactive content of the crustal cover; and

(*c*) on the rotation of the earth; upward moving currents will be deflected westwards and downward currents eastwards; in the northern hemisphere horizontal movements will turn towards the right and in the southern towards the left; such deflections, however, are likely to be very slight, and they will not be further discussed at present.

### The Planetary Circulation.

Considering the first of these we may infer by analogy with the atmosphere a circulation like that of the planetary system of winds. Within the earth the ellipticity of successive shells of increasing density gradually decreases with depth. Thus a considerable part of the difference between the polar and equatorial radii will be concentrated in the substratum. The equatorial thickness being greater than that beneath the poles, and the distribution of radioactivity being independent of latitude, the equatorial temperature gradient will be steeper than that towards the poles. Thus the general circulation from this cause should be as shown in Fig. 1.

As the equatorial ascending currents approach the base of the crust, they divide; half turning north and half south. As a result of the powerful drag thus imposed on the lower part of the crust the latter will flow with the currents but with a lower velocity, each level moving less rapidly than its underlying neighbour. The upper levels will tend to give way by fissuring or faulting as in the case of a glacier or ice-sheet. Thus the ultimate effect on continental blocks originally over the equator will be to drag them apart, leaving a depressed geosynclinal or oceanic belt along the equator. We have already seen that the early operation of the *Pohlflucht* force should have left the

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continents distributed symmetrically about the equator. The long history of the Tethys girdling the continental half of the earth between Gondwanaland and Laurasia is a clear indication of the operation of some opposing force tending to pull the continents apart. In the planetary circulation we have a first clue to its nature. The closing up of the Tethys is referred to the subsequent action of the sub-continental circulations.

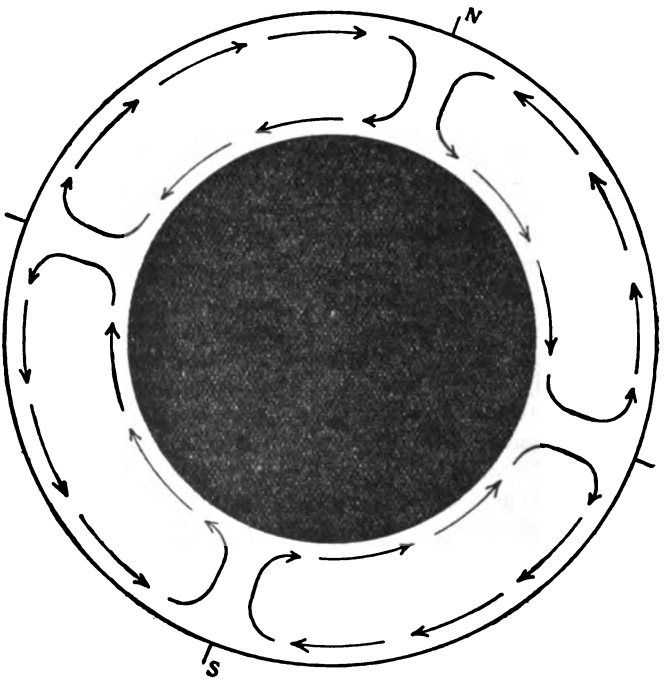


Fig. 1.[1]

## The Sub-Continental Circulation.

Superimposed upon the general planetary circulation there must be cyclonic and anticyclonic systems set up by the effects of regions of greater and less radioactivity in the overlying crust. Chief of these are the monsoon-like currents due to the distribution of continental blocks and ocean floors. Such evidence as we have, suggests that the radioactivity of continental rocks is

[1] For descriptions of figures see pp. 605-606.

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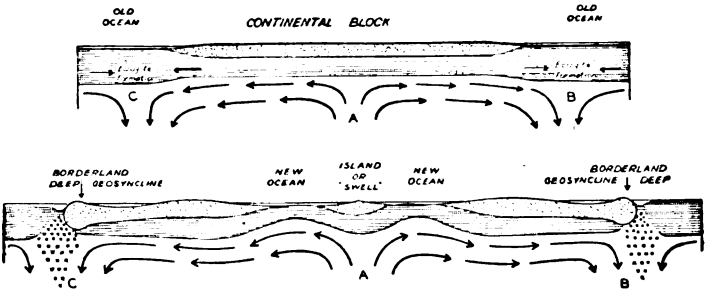
generally greater than that of oceanic rocks. Thus, although the temperature at the base of the crust will be everywhere nearly the same, the continental crust should be thinner than the old or normal oceanic crust, and thus beneath the continents the temperature should be higher than at the same level beneath the oceans. The circulation due to this unequal heating of the substratum would be a system of ascending currents somewhere within a continental region, spreading out at the top in all directions towards the cooler peripheral regions. The downward currents would become strongest beyond the continental edges where weaker currents from the oceanic regions would be encountered (Fig. 2).




Figs. 2 and 3.

In the simplest case the drag on the base of the continental crust would be radially outwards, but in reality the circulation would necessarily be more complex. Ascending currents would not generally be localised about a single centre, but rather about several centres and along previously thickened belts such as those of mountain ranges. In the peripheral regions, however, the currents would be everywhere directed towards the oceans.

In Fig. 3 an attempt has been made to represent the effects on a continental profile under ideally simple conditions. Where the ascending currents turn over, the opposing shears and the resulting flowage in the crust would produce a stretched region or a disruptive basin which would subside between the main blocks. If the latter could be carried apart on the backs of the currents, the intervening geosyncline would develop into a new oceanic region. The formation of a new ocean floor would involve the discharge of a great deal of excess heat. It will be

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shown later that the new crust will be more nearly basaltic in composition and more richly radioactive than the normal material of the substratum (p. 583).

We must next consider what will happen at the continental margins, or generally, where two currents meet and turn downwards. The crust above the zone of contact will be thrown into powerful compression and the amphibolite layer will tend to be thickened by accumulation of material flowing in from two directions. The observed effects of dynamic metamorphism at high temperature and differential pressure on such material lead us to expect that recrystallisation into the high-pressure facies, *eclogite*, will here take place on a large scale (25). The change of density from 2.9 or 3.0 to 3.4 or more, combined with the simultaneous operation of isostasy would lead to marked subsidence. Sinking of blocks of eclogite would also be facilitated by stoping promoted by the tongues of basaltic magma that would inevitably be present. Such foundering would effectually speed up the downward current for two reasons: the greater density of the sinking blocks, and the cooling of the substratum material in their vicinity.

Other possible consequences of eclogite formation will be suggested later; meanwhile we may notice that it provides a mechanism for " engineering " continental drift, and at the same time for discharging some of the excess heat generated in the substratum. Each part of the continental block would be enabled to move forward, partly by the fracturing and foundering of the belt of ocean floor weighed down with eclogite immediately in front, and partly by over-riding the ocean floor along thrust planes lubricated by magmatic injections from below.

The hypothesis of eclogite formation is supported by the fact that it provides a reasonable explanation of oceanic deeps. It is consistent with their depths, as judged from the requirements of isostasy, and with their occurrence in front of the active orogenic arcs bordering the Pacific on the Asiatic and Australasiatic side (53). That oceanic deeps are under compression is the opinion of Meinesz. He sees in downward flexure under stress a reason for the local defects of gravity revealed over deeps by his gravity surveys of the oceans. Evidence of the foundering of blocks is from the nature of the case not easy to find, but it may be forthcoming from the occurrence of deep earthquakes (arising from 100 km. or more) off the coast of

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Japan (86), and by the signs of volcanic activity that have been detected in the floor of the Tuscarara Deep.

The upper or sialic layer of the continental margin will also be thickened by the differential flowage of its levels towards the obstructing ocean floor. Here thickening of the crust and mountain building will occur, and the mountain roots, unable to sink, will begin to fuse and give rise to igneous activity of the Circum-Pacific type with basalt-andesite-rhyolite volcanoes. It has frequently been pointed out that, if the material of the ocean floor is weaker than that of the advancing continent, then mountain building will not take place; while if it is stronger, continental advance becomes impossible. With the mechanism here suggested this *impasse* does not arise. Mountain building occurs as a result of rock-flowage set in operation by the underlying current; it will generally occur provided that the horizontal component of flowage is greater from behind than in front. Deep-seated outflow of sial beyond its former margin appears to be involved in the great and geologically rapid uplifts indicated by the presence of abyssal deposits in the outer sedimentary zone of many island arcs (42). The forelands move like an ice-sheet, the upper levels being carried forward as a dead weight devoid of orogenic energy other than that which is derived from the active substratum below.

The effects of possible fusion and of differential flowage of the amphibolite layer remain to be considered. Since the outward transport of heat towards the periphery along any stream-line from the area where the currents ascend necessarily increases with the distance from that area, the currents will begin to fuse the base of the crystalline crust and a process of magmatic corrosion and transport will develop. This will become cumulative towards the periphery. At first the material undergoing fusion is likely to be peridotite, but sooner or later a point will be reached where partial fusion of amphibolite will occur. At the same time the lower layers of the amphibolite will be carried forward by rock-flowage more rapidly than those at higher levels. In part, the spilitic or basaltic magmas so generated may give rise to vulcanism above, but most of the magma should escape into the zone where the flowing amphibolite is being transformed into eclogite. There the magma will facilitate sinking of the eclogite blocks and lubricate the shear planes over which the continent advances. The place of the material removed

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from the amphibolite layer will be taken by the heavier material of the substratum, and, in accordance with isostasy, the region above will subside; that is to say it will become a geosyncline (50, p. 272). By the accumulation of sediments from the continent behind and the borderland or mountain arc in front, further subsidence of the geosyncline will occur. Thus the base of the crust will be kept hot, and may even grow hotter, and the process of geosyncline development will continue. It should be noticed that this region, though tending to subside, will nevertheless be under compression whenever rock-flowage in the underlying sial is more rapid than that in front. Thus folding may proceed concomitantly with subsidence and accumulation of sediments. This is well known to have occurred, but hitherto no explanation has been offered. Such geosynclines will be referred to as *interior* geosynclines. Those within the Asiatic island festoons are

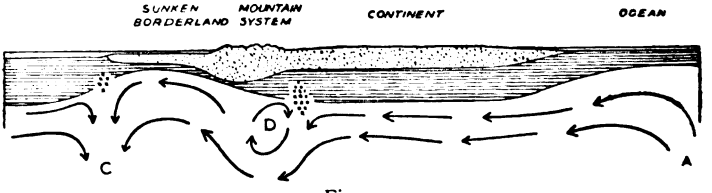


Fig. 4.

active examples. Compression associated with depression has been proved by recent geodetic measurements in the Kwansai District of Japan (100, p. 234).

Sooner or later a time will come when the buried crustal material beneath the infilled geosyncline will become hotter and weaker than the material behind and in front. Moreover, the grip of the underlying current will have weakened as a result of the higher temperature and lowered viscosity. At this stage thickening of the geosynclinal belt due to compression will become more effective than thinning by magmatic corrosion; mountain building will have set in (Fig. 4). The long history of the Cordilleran geosyncline of Western America, and its subsequent orogenesis (92), supplies a spectacular example of the process theoretically deduced. The Mesozoic and Tertiary history of Alaska tells the same story of long-continued subsidence interrupted and ultimately overcome by the effects of compression (85).

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Meanwhile the mountain roots will set up an accelerated transport of heat towards the continental edge, and the currents will thus move out far beyond the edge before beginning to descend. The borderland or mountain arc will then no longer be in the original zone where the horizontal component of rock-flowage is retarded against the belt of eclogite formation and deeps. Its lower levels will be stretched and thinned, and the area will subside as the interior geosyncline had previously done. Thus the disappearance of borderlands such as Cascadia—a phenomenon that has long been a puzzle to palæogeographers (92, p. 201)—may readily be understood. The hypothesis suggests that western America represents a more mature stage of development than eastern and south-eastern Asia.

To determine the velocities of the sub-continental currents under different circumstances is obviously highly desirable. Such rough estimates as I have attempted to make indicate a velocity of the order 5 cm. per year (50 km. per million years) as probable when the excess of temperature above that corresponding to the critical gradient is 10° C. On this conservative estimate the minimum period required to produce the Atlantic by continental drift would be some 100 million years.

The time taken for a block of eclogite to fuse completely is probably of the order 50 million years. Thus, sinking blocks should have nearly reached the bottom of the substratum before becoming entirely fluid, and streaks in the ascending currents should therefore be fed with magma much more nearly basaltic in composition than the general body of the substratum. The ascending currents will approach the surface in the region behind the advancing continent, and thus the new ocean floor is likely to receive the whole of the basaltic material available.

With ascending currents of such relatively light material, and descending currents made relatively dense by the presence in them of eclogite blocks, the whole circulation will be speeded up while continental drift is in progress. Moreover, the first effect of the formation of a new ocean floor will be in the same direction, since the crustal material previously there will be displaced by much hotter basic material. Later, however, the heat transported to the periphery of the continent and beyond will gradually prevent the formation of eclogite, and the zone of deeps will tend to migrate outwards and disappear. The magma representing what would otherwise have become eclogite

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will escape through the ocean floor in front of the edges of the sunk borderlands. The supply of sinking blocks having ceased, the current will slow down. At the same time the roots of the mountain system near the margin of the land will become the site of an opposing current (beginning as at D in Fig. 4), since there the heat output will have become greater than that of the continental crust behind. Moreover, as the new ocean floor cools, the ascending currents will fade out for lack of thermal sustenance. For a long time conditions will be chaotic, but gradually an entirely new convective system will evolve tending to close up the continents again. The approach of Africa and Europe across the site of the Tethys is the most striking example of this inevitable reversal of circulation brought about by the changing boundary conditions of an earlier system of currents.

## VI.—SOME GEOLOGICAL CONSEQUENCES.

### Continental Drift.

Turning now to the effects of a radial sub-continental system of convection currents as visualised in plan, it is easy to see that each great continental block—such as Laurasia or Gondwanaland as they were at the close of the Palæozoic—should tend to break up into smaller blocks. The latter will drift radially outwards, leaving disruptive basins behind and between, and having geosynclines and borderlands in front, represented later by mountain systems and sunk borderlands.

In the case of Gondwanaland the evidence of late Carboniferous glaciation is here accepted as a definite geological proof that such drifting has since taken place. As I have already briefly reviewed the whole problem in a recent paper (54), the ground need not here be gone over again. It is desirable, however, to direct attention to later discussions by Thomas (101), Walton (105) and Cotter (20), which indicate that in New South Wales, Rhodesia, South-West Africa and India, the glacial beds are all nearly contemporaneous and of probably late Carboniferous rather than early Permian age. Simpson has shown from the meteorological standpoint that glaciation of regions now in or near the tropics "could not possibly have been brought about by any rearrangement of land and water," and he is forced to conclude that "there has been a considerable shift of the continents relative to the poles and the climatic zones" (95, pp. 22

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and 23). The deduction cannot be escaped that South Africa lay near the South Pole and, if verification be required, it is to be found in the distribution of Upper Carboniferous laterites recorded by Harrassowitz (39).

But, this being granted, we must envisage not only a radially outward drift of each great land mass towards the Pacific and the Tethys, but also a general drift, possibly involving the *whole* of the crust, with a northerly component on the African side sufficient to carry the South African region from the South Polar circle, and Britain from the tropics, to their present positions. This picture is rather different from Wegener's, but it is believed to be a reasonable statement of the movements that occurred. Here, then, we have a severe test of the convection hypothesis. Can it provide a northerly drift for the African hemisphere?

In Fig. 5 the combined effects of the two types of circulation so far considered are represented for the time at which the movements leading to our present geography began. A quantitative treatment is at present impracticable, but a roughly qualitative assessment is possible on the assumption that the sub-continental circulation becomes stronger than the planetary circulation. In Gondwanaland the chief ascending current would most probably develope near the Cape Mountains and their continuations. Thus the planetary circulation would be completely reversed beneath Gondwanaland. In Laurasia the chief ascending currents would be along the Appalachian—Caledonian belt, modified in Europe by the eastward divergence of the Hercynian ranges, and the planetary circulation would thereby be strengthened in the north but reversed in the south. The resultant forces (as represented in Fig. 5) would clearly be in the direction of rotating the whole crust towards the north on the land hemisphere and towards the south on the Pacific side.[1] The success of the hypothesis in providing a possible mechanism for this long-puzzling movement goes far to justify its tentative acceptance.

The hypothesis has other significant implications. It indicates that superimposed on the general crustal drift there would be a relative approach between Africa and Europe. This would be intensified by the resultant of the currents from the hot regions beneath the growing Indian and South Atlantic Oceans.

[1] For the long-distance transmission of thrusts through the crust see Goldstein (31).

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Although these currents would be directed towards the interior of Africa, and would thus place Africa under compression, the resultant would be a drive in a northerly direction. Here we have exactly the conditions postulated by Argand and other Alpine geologists as essential to account for the structure of the Alps.

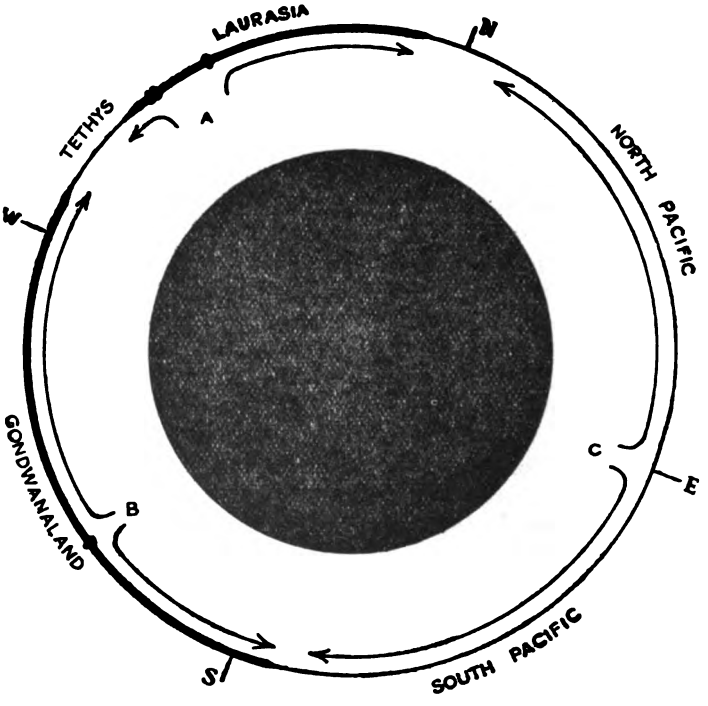


Fig. 5.

The northerly drift of India would seem incredible if it were not implied by the facts (*a*) that in the late Carboniferous India was glaciated from the south; (*b*) that it became an active site of laterite formation from the Eocene onwards; and (*c*) that the

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Himalayas and Tibet, from being a depressed marine area have become the highest mountain-flanked plateau on the face of the earth. The very powerful drag that would be necessary to effect the movement and the enormous thickening of the crust to the north implies an unusually vigorous current. The latter can reasonably be referred to the growth of the Indian Ocean, for this would greatly intensify the currents that initiated its formation. As India pushed through the Tethys geosyncline, much of the underlying amphibolite layer would be recrystallised into eclogite and sunk. Only in this way could the great excess of heat that would otherwise have accumulated beneath Tibet have been discharged. Isostatic considerations suggest quite independently that the sial or upper layer of Tibet and the Himalayas must greatly exceed the normal thickness and that the amphibolite layer is likely to be very thin or represented by eclogite. The region is one that may be expected to become the seat of uprising currents that will lead in the future to earth movements and batholithic intrusion on a gigantic scale.

The position of Australia, and the unusual width of the depressed area that separates it from the Australasian arc, are consistent with the assumption that the currents from the Indian Ocean substratum were particularly vigorous. Australasia had not to meet the full resistance—thermal as well as mechanical—of a continental block like Asia, and so, as we find, it travelled even further away from its original site than India did.

Antarctica, on the other hand, was moved in the face of the southward currents of the South Pacific substratum and therefore was unable to drift so far away from the neighbourhood of Africa. Originally it probably lay on the Pacific side of the South Pole, but the general crustal drift already described (Fig. 5) carried it polewards.

No ocean has yet formed between Asia and Europe, although, as Argand has pointed out, the region from the Caspian and Aral Seas to the Obi basin is a relatively depressed one. Presumably the tendency to powerful currents was slight, corresponding to the fact that the Asiatic coast lands are in a much less advanced stage than those of North America. Moreover, the bodily thrusting of the northward extension of India beneath the Tibetan area may have created a thermal resistance which would prevent the normal development of currents beginning to move outwards from the Khirgiz Steppes.

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## Peripheral Mountain Systems.

Taylor and du Toit have both drawn attention to the orogenic rings corresponding to the dispersive movements of Laurasia and Gondwanaland. In Figs. 6 and 7, I have represented these rings on a projection for which I am indebted to my former colleague, Prof. J. M. Holmes.

Laurasia is thought to have spread outwards towards the Pacific and the Tethys, and it is surrounded to-day by the orogenic ring of the West Indies, the Cordillera of North America, the Asiatic Island festoons and the northern side of the Alpine-Himalayan system. Within it lie the great disruptive basins of the Arctic and North Atlantic Oceans. The arrows in Fig. 6 indicate approximately the directions of continental movement implied by the structures of the ranges. For the Tethys-belt Argand's bold diagrams clearly illustrate the conception that ranges thrust over a foreland from a geosyncline imply an underthrust of the foreland in a direction having a component opposed to that of the surface overfolds and nappes (9). As in the case of compression of a plastic substance between the closing jaws of a vice, so here the energy is supplied by the movements of the forelands; and as the vice is actuated by an external source of energy, so here the forelands are carried forward by deep-seated rock-flowage maintained by currents in the substratum.[1]

Sub-continental flowage from Asia towards the Pacific may be inferred from the échelon structure of the island festoons. The remarkable analysis of the latter by Tokuda (102) and his Japanese colleagues (29), and his success in imitating the structures by simple experiments, have revealed the operation of active agents from the interior of the arcs, as originally surmised by Suess. In each case the maximum movement has been towards the middle of the arcs, becoming gradually less towards the more stable buttresses (Kamchatka, Yezo, Formosa, etc.) between successive arcs. This line of attack has been developed by Lee and applied to the tectonics of Asia as a whole (79, map p. 511). Outward movements have been deduced by Brouwer from his observations relating to the mountain building now in progress in the Banda arc (13). The forward flowage of sial is evidenced by the Tertiary charges of level in Java described by Martin (84, p. 14), and by the great and geologically rapid uplifts of the outer zones of many growing island arcs to which Hobbs has repeatedly directed attention (42).

[1] For an experimental illustration of this type of process see Bull (16, pl. 10).

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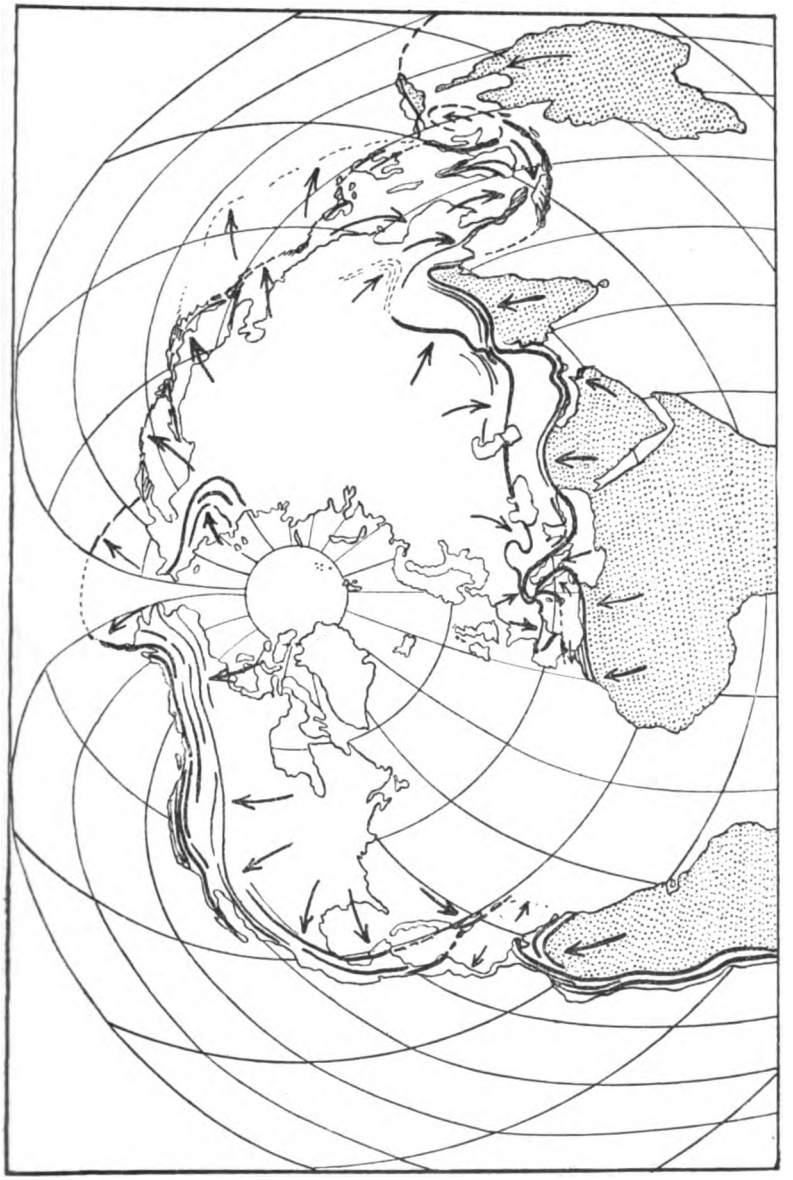

Fig. 6. *Scale*: 1 : 170 x $10^6$.

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E. C. Andrews has made a valuable comparative study of Australasia, China and Japan, and North America, and despite the fact that on the American side the structures are now closely telescoped, he has made it clear that there has been a marked outward growth of each of these terrains towards the Pacific. With advancing time, from the Pre-Cambrian onwards, the ore-deposits appear in zones successively nearer the present periphery, as if there had been an outward spread of material (6). The more complex Antillean region has recently been dealt with by Schuchert (93) and is referred to below.

In Gondwanaland the movements appear to have been at first radially outwards from the neighbourhood of southern Africa, and afterwards, as they developed, from the South Atlantic and Indian Oceans. Here we have the broken orogenic ring of the Venezuelan Andes and the South American Cordillera, the Antarctic Andes, the New Zealand and New Guinea mountains of the Australasian arc, the Himalayas, north of India, and the southern side of the Alpine system, north of Africa (Fig. 7). Observations in Peru (110) and Colombia (36, p. 164) have revealed thrusting from the Pacific and Antillean sides, indicating an outward movement for South America. Henderson has recently presented evidence for regarding the north-east trending crustal ridge, of which New Zealand is the highest part, as the upthrust edge of a gigantic crustal block with its frontal scarp overlooking the Tonga Deep (40). For New Guinea and Antarctica there is, as yet, little detailed evidence, but the mountains are just where they would be expected on the continental drift and convection current hypotheses here developed.

## Geosynclines.

In 1927 I discussed the physical conditions under which geosynclines could be formed and concluded that "the only known causes competent to produce geosynclines in which the original floor has subsided to great depths are (*a*) migration of light magmas from the geosynclinal column into the bordering regions; and (*b*) thinning of the original *sial* layer by stretching; in each case accompanied by a compensating inflow of heavy material from greater depths" (50, p. 272). To these I added (*c*) increase of density due to metamorphism of the underlying material, as a subsidiary cause. The convection hypothesis provides a mechanism for each of these.

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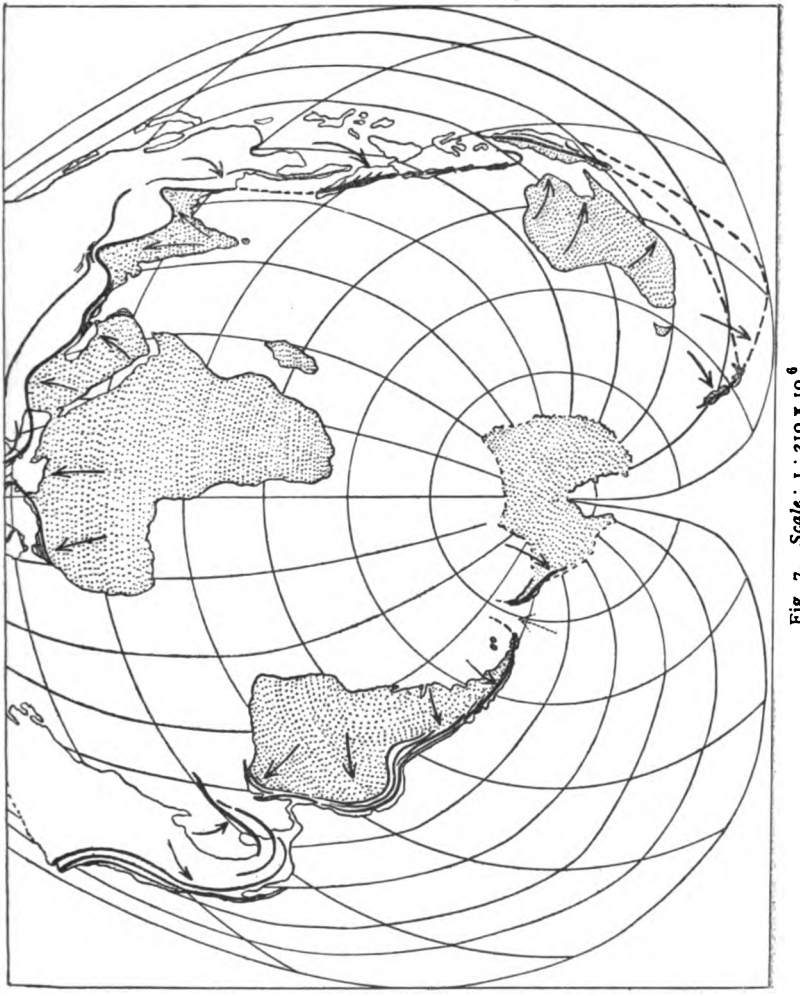

Fig. 7. *Scale*: 1 : 210 × 10.[6]



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Type (*a*) is here referred to magmatic corrosion and flowage of the amphibolite layer; it has already been described as the "interior" type of geosyncline on page 582, where it was shown that it would commonly be developed under conditions of compression. Each continental block has, or has had, one or more examples of this type. Most familiar are the seas within the Asiatic festoons from the Behring Sea to the Java Sea and beyond to the Riverine tract of Burma. On a far greater scale are the depressed areas of the Coral and Tasman and Arafura Seas of Australasia. Antarctica has its representative in the Weddell and Ross Seas. The corresponding African feature is probably to be seen in the Eastern Mediterranean and the Adriatic, though here additional complexities have entered. The long-lived composite Cordilleran geosyncline of North America provides the greatest known example of geological history (92). The Gulf of Mexico is probably in part a geosyncline of similar origin. South America and Europe have also had their interior geosynclines, though now they are, for the most part, closed up or uplifted by subsequent compression.

Type (*b*) is that due to the distension of a continental block or the separation of two such blocks by diverging currents. The Tethys is the greatest example of the latter case, and the opening of the Uralian geosyncline in the Lower Devonian illustrates the former. Ocean basins evolve from the long continued operation of the process.

Type (*c*) is represented by a special kind of median area lying between opposed mountain systems bordering approaching forelands. The Caribbean Sea, the Western Mediterranean and the Banda Sea are examples. These are all in regions where sub-continental currents approach and throw the nearly sial-free crust into compression.

Still another type of geosyncline, also referable to (*c*) remains for consideration; the type that forms on the foreland side of a growing mountain system. There are many present-day examples: the Indo-Gangetic trough; the Persian Gulf and the Tigris-Euphrates valley tract; the Schotts depression south of the Atlas; the fore-Caucasian sunkland from the Caspian to the Sea of Azov (90); the Orinoco valley south of the Venezuelan Andes; and in part the Adriatic-Po valley depression and the Eastern Mediterranean. The latter area has already been mentioned as an interior geosyncline of type (*a*). It is a region of

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composite origin and its tectonics are correspondingly complex. The pure type is well represented by the Indo-Gangetic trough, and it differs from type (*a*) in developing during the compression of type (*a*); Grabau describes the phenomena as " the migration of geosynclines " (32). Whereas type (*a*) is due to the thinning of the amphibolite layer, the new bordering geosyncline forms as a result of the compression that transforms type (*a*) into a mountain system. As the amphibolite layer continues to flow towards the mountain roots it meets there an obstruction (above D in Fig. 8) and is transformed into eclogite. Thus the region bordering the mountains becomes depressed. Sediments accumulate and may in their turn become steeply folded. An excellent example is to be found in the Soan geosyncline (now folded) of Poonch State in Kashmir, recently described by Wadia (103). Here there is a continuous record of 20,000 feet of sediments ranging from the early Miocene to the middle Pliocene, indicating very marked subsidence during the time when the Himalayan folding was at its height.

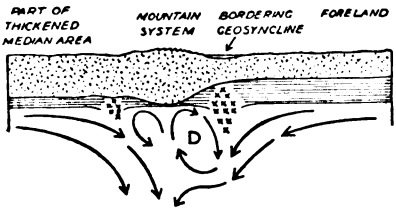

Fig. 8.

Thus it appears that convection currents, co-operating with eclogite formation in the appropriate belts, are competent to account for all the varieties of geosynclines that have been recognised.

## Median Areas.

As Kober has emphasized in the case of the Alps, two opposing mountain systems are commonly overturned away from each other with a more or less broad *zwischengebirge* or median area between. The median areas range from high plateaus like Tibet through regions such as Persia and the Pannonian basin to deep seas like the Western Mediterranean and the Caribbean Sea. The case of Tibet is a result of enormous thickening of sial (Fig. 8) due to the underthrust of India accompanied by the disappearance of most of the amphibolite layer. The Western Mediterranean and its analogues represent relics of the Tethys floor which had probably very little sial covering when the approach of the continents began. The intermediate examples

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mentioned above may possibly have been sial patches forming "swells" in the original Tethys. As the forelands approached, the zones of eclogite formation would also approach and unite beneath the sial patches. The colliding mountain arcs on either side of the median area would protect it from superficial compression, and hence it may even have subsided while the enclosing ranges were being pushed over their respective forelands. Such was the case in the Pannonian basin within the Carpathians (36, p. 160). Afterwards there might develop a thickening of the area (*plis de fond*) as a result of continued deep-seated inflow of amphibolite.

When median areas are compressed, the stream-lines of rock-flowage will tend to swerve round at right angles to their original directions wherever there is a lateral inferiority of resistance (Fig. 9). This should be particularly noticeable where approaching continents have an ocean on one or both sides, e.g. in the case of North and South America. The lateral stresses directed against the ocean floor will develop thrust planes increasing in steepness as the more rigid upper levels of the crust are fractured. In plan the thrust planes will be convex towards the oceans. Magmas will escape up the curved fractures and form volcanic belts or arcs of islands at the surface. In this way the Panama-Costa Rica land bridge and the volcanic arc of the Lesser Antilles can be readily explained. No difficulty stands in the way of the generation of magmas—basaltic, andesitic or rhyolitic—for median areas are destined by their position with regard to the advancing currents to become foci of heat concentration. The Persian and Pannonian median areas are partly girdled with Tertiary volcanoes. The peripheral volcanoes of the Caribbean have been already referred to. A similar arrangement of volcanic arcs is to be found around the Western Mediterranean (42) and the Banda Sea.

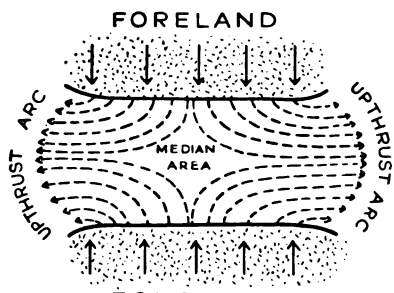

Fig. 9.

The sea enclosed by the Southern Antilles between Antarctica and Patagonia is not a true median area, since Antarctica and

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South America have separated rather than approached. The island arc here is probably a lag effect due to a strung-out belt of sial having been dragged against part of the Pacific floor left between the two continental blocks as they advanced. Corresponding to this interpretation there are volcanoes and deeps on the eastern side where the substratum currents from the Atlantic and the Pacific meet squarely, but on the western side there is nothing corresponding to the Panama volcanic ridge of Central America since there is no pressure between Graham Land and Tierra del Fuego (57).

## Rift Valleys.

The convection hypothesis suggests the possibility that rift valleys are the surface expression of narrow elongated median areas of a very special type. A vast area of south and eastern Central Africa was reduced in pre-Tertiary times to a peneplain which has since been uplifted through hundreds and even thousands of feet. As Wayland infers: " this bulging suggests very deep-seated compression " (107). It has already been indicated that the northward drive of Africa was probably the resultant of substratum currents moving in from beneath the Indian and South Atlantic Oceans. A source of compression for the great *plis de fond* of High Africa is thus available. Wayland also points out that the site of Lake Victoria was formerly a watershed of domoid form, and he considers that the subsidence which led to the formation of the Lake depression was contemporaneous with the appearance of the nearly encircling rift valleys. The Victorian bulge may well have started a subsidiary system of currents as the sial layer thickened, and it is here suggested that the rift valleys lie over the belts of eclogite formed where the Victorian system of radial currents met the two sets of currents coming in from beneath the growing ocean floors (Fig. 10). To the south the latter would impinge directly, but to the north the Victorian currents would reinforce the northward drift so that the Western rift would die out, whereas the Eastern would continue. The currents would not be directly opposed. So long as they converged they would meet along a line, like the currents producing a line-squall in the atmosphere. Along this line eclogite would form from the amphibolite material flowing in. At the same time the tendency of the sial on either side to advance would lead to the development of curved thrust surfaces steepening towards the surface, as already visualised

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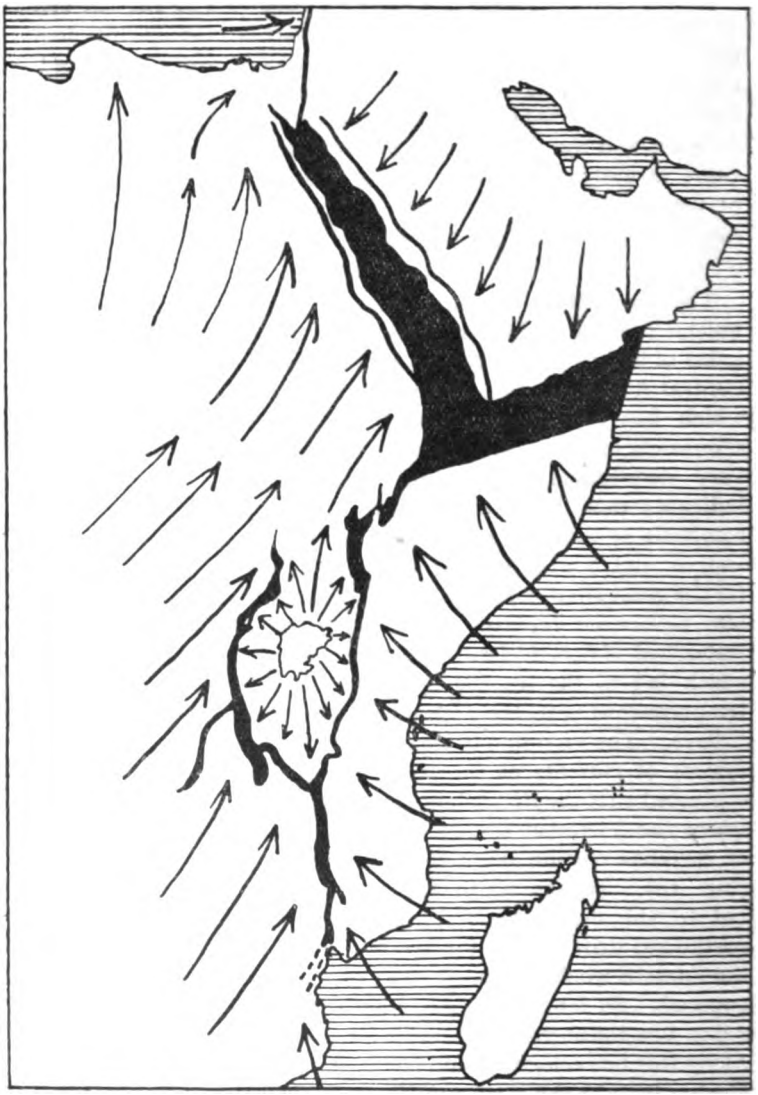

Fig. 10.

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by Wayland (106). The crust would move forward and upward on these surfaces and would thus come to be tilted away from the zone where the fractures outcropped. Superimposed on this effect would be the subsidence due to eclogite formation, this being greatest in the middle and systematically less towards the sides. Figs. 11 and 12 illustrate the processes invoked and

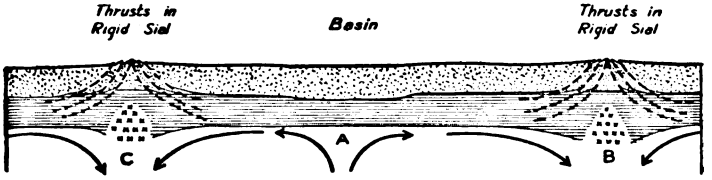


Fig. 11.

the structures produced. The mechanism is like that of cauldron subsidence, but elongated along a line instead of being centrally over a magma-chamber. Magma would, of course, be present, as always where heat-conveying currents approach. It would occupy spaces left by the sinking of blocks of eclogite, and its subsequent displacement and contraction on cooling would contribute to the many accessory phenomena associated with rift valleys. The subject is not one that can be discussed briefly to any further advantage, and a fuller discussion, including that of the very interesting petrological implications, must be reserved for another occasion.

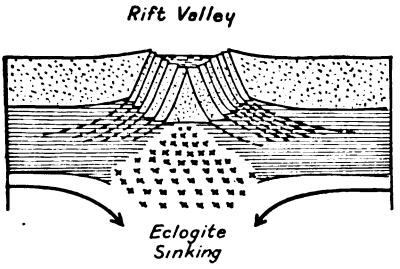


Fig. 12.

To explain the Gulf of Aden and the Red Sea on this hypothesis it seems necessary to assume that the older currents directed southwards from the Tethys did not die out beneath Arabia until after the newer Gondwanaland system had become active. It is noteworthy that the Red Sea had already formed when Arabia began to push against the geosyncline from which the Zagros Mountains were raised. After the first subsidence of the Red Sea and Gulf of Aden there would be a downward protrusion of the sial layer relative to the lower surface of the

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surrounding sial of Egypt, Arabia, etc. (as in Fig. 12). As the Gondwanaland currents drove back the weakening Tethys currents, much of this protrusion would be carried under Arabia by rock-flowage. Thus the Red Sea and the Gulf of Aden would continue to subside, and the plateau of Arabia would be produced by uplift consequent upon the addition of sial to its original sial layer. It must be clearly realised that the currents marked in Fig. 10 as flowing southwards from the Tethys region were later reversed. (See Figs. 6 and 7).

The whole problem of rift valleys is so difficult that it would be idle to pretend that anything more than a promising clue has been suggested. Examples such as the Dead Sea trough and the Rhine Graben may later fall into line, but at present speculations regarding their origin cannot be offered with any confidence.

## Changes of Level of Land and Sea.

In his recent Presidential Address on the Pacific Gregory writes, "The direct geological evidence is overwhelming, that large blocks of the earth's crust rise and fall for vertical amounts greater than the greatest depths in the oceans. If continental blocks cannot sink, much geological evidence becomes meaningless" (34, p. cxxxii). The convection-current hypothesis provides adequate processes to account for the great changes of level that have taken place. The replacement of the amphibolite layer by heavier peridotitic material could provide up to 3 or 4 km. of subsidence. Sunk borderlands, such as those off North America (92), Peru (97), the South Coast of Java (84) and the North Coast of New Guinea (111), may all be referred to the action of this process. The disappearance of other continental areas, like the old Atlantic lands, may be readily accounted for by continental drift and the gradual development of new ocean floors. Still greater depths require the substitution of eclogite or peridotite for the gabbro-amphibolite material of the ocean floor. Great vertical uplifts are brought about by the thickening of the sial layer as in Tibet and Arabia, or by the outward flow of sial from the continental crust to the outer zones of peripheral island festoons. Similarly, mountain roots may be carried laterally away from their place of origin, resulting in lowering of the mountains and uplift of the regions in front. Obviously, with the four kinds of material, sial, amphibolite or gabbro, eclogite, and peridotite, combined with all the phenomena of convection, rock-flowage, fusion and crystallisation, the possi-

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bilities of changes of level and lateral movements are sufficiently varied to meet all the valid requirements of geological history.

The explanation of marine transgressions offered by Joly's hypothesis of thermal cycles has been generally regarded as one of its most attractive features. Under the convection hypothesis the conditions for marine transgressions are less regular and of less embarrassing amplitude (48, p. 536). While continental drift is in progress the old ocean floors immediately in front are sinking, and the heavy blocks of eclogite follow a path that carries them beneath the advancing continents. Thus the latter will sink a little, rising later as the sunken blocks gradually fuse. Behind the continents the material of the new and growing ocean floor is at first hot and expanded as compared with its later condition after cooling. This implies a relative rise of the ocean floors while they are hot, and consequent spilling over of the water above. The combined effect of these two processes will be marked transgression while continental drift is active. Recessions should follow as the drifting gradually slows down. The actual events since the close of the Palæozoic match the deduction in a general way. With many fluctuations the transgressions reached their maximum in the middle Cretaceous, falling away with the late Cretaceous mountain building, expanding again during the Eocene, and finally withdrawing as Recent time was approached. There are many reasons for fluctuations: geosyncline development, mountain building, sinking of borderlands, and rising and falling of median areas all produce marked local changes and smaller world-wide reactions. Sedimentation implies a displacement of water. Movements of continents towards the equator retard the earth's rotation and lead to the spreading of seas in high latitudes with recession in low latitudes. Conversely, if continents drift polewards the opposite effects are produced. These consequences are due to the immediate response of the water surface to changes of rotation, and are reversed as the geoid slowly accomodates itself. The accumulation of ice-sheets lowers the sea level and melting of the ice raises it. Isostatic adjustments imply minor modifications. Clearly the interplay of possibilities is very varied, and the analysis of the actual facts is not likely to lead to sound conclusions until the study of world stratigraphy has advanced far beyond its present beginnings.

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## VII.—CONCLUSION.

It is not to be expected that the first presentation of a far-reaching hypothesis and its manifold applications can be wholly free from errors. The workings of the inner earth reveal themselves only indirectly, and their actual nature in space and time is certain to be far more complex than can be visualised. Nevertheless, the preliminary survey that has here been given seems to show that the convection-current hypothesis goes far to account for

(*a*) the leading features of continental drift since the close of the Palæozoic;
(*b*) mountain building and island festoons;
(*c*) oceanic deeps;
(*d*) the initiation and development of geosynclines of various types under both compression and tension;
(*e*) the growth and disappearance of borderlands;
(*f*) the varied characters of median areas;
(*g*) rift valleys;
(*h*) the distribution of earthquakes;
(*i*) igneous activity and the distribution of volcanoes;
(*j*) marine transgressions and recessions; and
(*k*) possibly the maintenance of the earth's magnetism.

So far the treatment has been almost entirely qualitative and therefore it inevitably stands in need of criticism and quantitative revision. The hydrodynamics of the substratum and its behaviour as a heat engine need to be attacked on sound physical lines. The capacity of substratum currents to promote magmatic corrosion, transport and crystallisation, and to produce migrating sub-crustal wave forms, calls for detailed treatment. The full bearings of the hypothesis on petrogenesis have yet to be investigated. Meanwhile its general geological success seems to justify its tentative adoption as a working hypothesis of unusual promise.

This paper is based on a lecture delivered before the Society on 12 Jan. 1928 and summarised in the Geological Magazine (51). Advantage has been taken of the delay in writing up the material to incorporate references to papers which have appeared since the date of the lecture.

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## DESCRIPTION OF FIGURES.

Fig. 1, p. 578.—Planetary circulation of the substratum (crustal effects being ignored).

Substratum, white. Metallic core, black.

Fig. 2, p. 579.—Sub-continental circulation.

Upper or sial layer, dotted. Intermediate layer (amphibolite, gabbro, etc.) line-shaded. Substratum, unshaded.

Fig. 3, p. 579.—Distension of the continent on each side of A leaving an island or "swell" in the "dead" area above A. Above B and C eclogite formation results from the crystallisation of the material of the intermediate layer, and oceanic deeps are produced. The front part of the sial is thickened and a borderland results. Behind this, one effect of the heat transport from A to B or from A to C is the development in each case of a geosyncline.

Fig. 4, p. 582.—The geosyncline has been compressed into a mountain system above D where a new system of currents begins. The outward current towards C is strengthened and the borderland is stretched out and becomes a sunk-land. The opposing current at D leads to the formation of a bordering geosyncline as shown in Fig. 8.

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Fig. 5, p. 586.—Convection currents (Triassic time), illustrating the dominance of the clockwise direction and the resulting northerly drift of the land hemisphere.

A. Ascending currents controlled by the Hercynian and Caledonian thickening of the crust. (In North America these two belts more nearly coincide than in the diagram).

B. Ascending currents controlled by the Cape Foldings, previously formed during the growth of the Tethys.

C. Ascending currents of the planetary circulation beneath the Pacific.

Fig. 6, p. 589.—Orogenic " ring " and continental movements of Laurasia. (The adjoining blocks of Gondwanaland are dotted).

Fig. 7, p. 591.—Orogenic " ring " and continental movements of Gondwanaland (dotted).

Fig. 8, p. 593.—Illustrating the formation of a bordering geosyncline (e.g. Indo-Gangetic trough) between a mountain system (e.g. Himalayas) and its foreland (e.g. Peninsula India).

Fig. 9, p. 594.—Stream-lines of rock-flowage in the lower crustal levels of a median area between two approaching continental blocks: to illustrate the formation of upthrust arcs, generally surmounted by volcanic islands, convex in plan towards lateral areas relatively deficient in resistance.

Fig. 10, p. 596.—The rift valleys of Africa (after Gregory, 35) with hypothetical substratum currents indicated by arrows. The currents beneath Arabia are to be regarded as a survival of the Tethys system which was later reversed by the growing activity of the Gondwanaland system. The Arabian part thus represents an earlier period than the rest of the diagram.

Fig. 11, p. 597.—Hypothetical section across the Victorian area of the African bulge. Subsidiary currents due to the latter ascend at A and produce the Lake basin above. Descending currents at B and C are responsible for stresses that produce thrust planes above (broken lines) and eclogite below (crosses), thus localising the sites of the Eastern and Western Rifts.

Fig. 12, p. 597.—Illustrating the formation of a rift valley by subsidence of the sial over the belt of eclogite formation. It should be noted that in Figs. 11 and 12 the opposing currents have generally a northerly component not representable in the plane of the diagrams.

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No. XIX.—TRINUCLEUS IN THE GIRVAN AREA. By JAMES L. BEGG, F.G.S. Read 14th February, 1929; Issued July 23rd, 1931.

THE genus *Trinucleus* indicates Middle and Upper Ordovician. One species is recorded from the Balclatchie of Dow Hill, Girvan (Upper Llandeillo), several species from the Whitehouse group of Whitehouse Bay and Shalloch Mill (Middle Bala), and one from the Drummuck beds of Thraive Glen and Quarrell Hill (Upper Bala).

Three species have been described and figured by Dr. F. R. Cowper Reed (1906),[1] but only one of these is completely known, *T. bucklandi* Barrande. This form is abundant in the Drummuck beds in all stages of growth. From the Whitehouse group Dr. Reed (*op. cit.*) figures and describes seven species, but as these are represented only by head-shields or pygidia, it has been considered premature to give them specific determinations and they appear as *Trinucleus* spp. a-g. With the aid of better material collected by the late Mrs. Gray, Dr. Reed has defined with greater precision the characters of *Trinucleus* sp. b. in a supplement (1914)[2] to the 1906 paper. *T. albidus* Reed, but definite knowledge of the thorax is still lacking.

The species from the Balclatchie of Dow Hill (see figure) is *T. subradiatus* Reed. This little trilobite is not at all rare here, but is not recorded from any other locality. Owing to the lack of well preserved material Dr. Reed's description is practically confined to the head-shield. In later works[3] dealing with the head-shield (glabella and fringe) in the genus *Trinucleus*, Dr. Reed gives more detailed descriptions of the pitted nature of the fringe, girder of the lower lamella of the fringe, glabella and "occular tubercle" in *T. subradiatus*.

In recent years I have secured quite a number of specimens from the small exposure at Dow Hill. Among these there are casts of thoracic segments, enrolled specimens, and one perfect but detached pygidium.

In the original description of the head-shield, Dr. Reed says; "occipital ring broad at centre produced backward into a short triangular nuchal spine." I find that this triangular area only covers the first axial ring and is merely the base or proximal end

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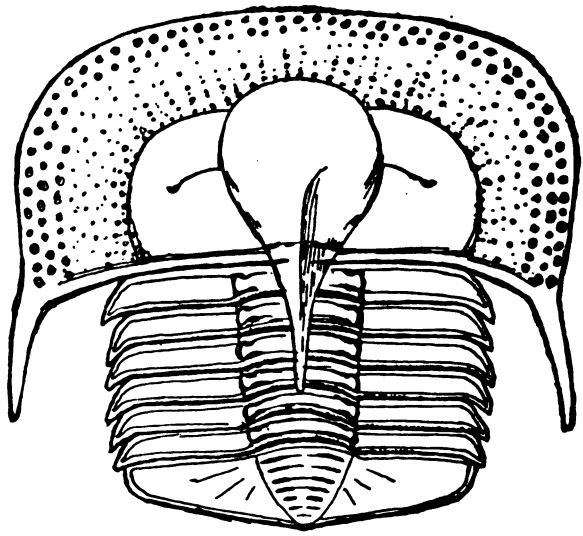
of a spine that equals in length the spines at the genal angles; it extends to and covers the fourth body segment.

*Thorax*:—Considerably narrower than the head-shield with fringe; six segments; axis cylindrical, prominent, about one-fourth the width of the thorax; the grooves in the axial rings are slightly pitted on each side; pleural segments straight, horizontal, with broad median longitudinal groove, bordered by well rounded elevated margin; the ends of the pleurae are pointed and bent downwards and backwards.



TRINUCLEUS SUBRADIATUS.

The thoracic segments appear to resemble those of *T. bucklandi* Barrande, and *T. gibbifrons* McCoy. The thorax conforms to the generic type. Specific distinctions are based on the characters of the head-shield and pygidium.

I have no doubt that the isolated pygidium is referable to *T. subradiatus* Reed, from field evidence, and because the conical deeply grooved axis is found also in the crushed pygidia of enrolled specimens. I submitted this specimen with several others to Dr. Reed, and he says in a letter " I do not think there can be much doubt that your No. 7 is a pygidium belonging to this species."

*Pygidium*:—Sub-triangular rather than semi-circular in plan.

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marginate with narrow rounded border; postero-lateral angles rounded. It is five times broader than long. Axis convex, conical, about one-fourth the width of pygidium, extending to the posterior extremity; it is deeply grooved and the rings are more numerous than the ribs on the lateral lobes; these are very faintly marked, apparently three in number, and directed obliquely backward.

The two outer rows of pits on the fringe and those of the third row near the genal angle show a great contrast in size with the small inner pits. This feature has been regarded as the most distinctive characteristic of *T. subradiatus*. The glabella has features in common with *T. lloydi* Murchison, *T. concentricus* (Eaton), and also with the American form *T. reticulatus* Ruedemann. The long nuchal spine is an additional feature differentiating *T. subradiatus* from allied species of the genus. The pygidium shows a feature common to certain families of trilobites, a gradual increase in the number of axial rings posteriorly without a corresponding increase in the number on the lateral lobes. This phenomenon is considered by some palaeontologists to indicate a late stage of development and to be of a phylo-gerontic nature. Richter (1925) states that in the Permo-Carboniferous form *Anisopyge perannulata* (Shumard), one of the latest species of the class, there are about 30 rings on the axis with only 8 on the lateral lobes. This is a matter which cannot be discussed here.

[1] "The Lower Palæozoic Trilobites of the Girvan District, Ayrshire," Part III, *Monogr. Palæontogr. Soc.*, lx. pp. 97-186.

[2] "The Lower Palæozoic Trilobites of Girvan," *Supplement, Monogr. Palæontogr. Soc.*, lxvii, pp. 1-56.

[3] "Genus Trinucleus," *Geol. Mag.*, vol. 49, 1912, pp. 348, 351, 386, 394; *Ibid.*, vol. 51, 1914, p. 358; *Ibid.*, vol. 53, 1916, p. 121.

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## PROCEEDINGS OF THE GEOLOGICAL SOCIETY OF GLASGOW SESSIONS, 1927-1931.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 14TH APRIL, 1927.

The seventh meeting of the sixty-ninth session—Mr. MURRAY MACGREGOR, *President*, in the chair.

The President read a paper "Some Geological Notes on three Districts of Northern Scotland," by A. G. Steavenson, M.A.

The communication comprised three short papers—(1) "The Stornoway Torridonian Outlier"; (2) "Some Foliated Granites in Western Lewis"; (3) "The Geology of the Stromness District, Orkney Islands." *See* Vol. xviii, Part 1.

Mr. McLean expressed his appreciation of the papers, and asked the President to convey to Mr. Steavenson the thanks of the meeting. Mr. Holmes and Mr. Begg drew attention to the fact that the Society's Vice-President, Mr. A. Stevens had assigned a Triassic age to the Stornoway deposits.

A. STEVENS.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 13TH OCTOBER, 1927.

The first meeting of the seventieth session was held here this evening—Mr. A. STEVENS, *Vice-President*, in the chair.

Mr. J. E. Richey read a paper on "The North Ayrshire Sequence of Calciferous Sandstone Volcanic Rocks." *See this Volume*, Part II.

Dr. G. W. Tyrrell congratulated Mr. Richey on his paper. He had stated that the trachytic types were later than the others. This was consistent with the speaker's observations in other parts of the Western district. The trachytic vents of Meikle Bin and Misty Law had broken through the basalt plateaux of the Campsies and Renfrewshire. In 1917 he had correlated the trachytic dykes of the Cumbrae with that phase. More recently, Mr. McCallien had established the same sequence of basaltic and trachytic rocks in the Campbeltown district.

Mr. Murray Macgregor delivered Part I of his Presidential Address on Scottish Carboniferous Stratigraphy. *See this Volume.*

M. MACGREGOR.

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SOCIETY'S ROOMS, 207, BATH STREET, 10TH NOVEMBER, 1927.

The second meeting of the seventieth session was held here this evening—Mr. MURRAY MACGREGOR, *President*, in the chair.

*Annual Business Meeting.* Reports of the Council, Finance and Library were read by the Secretary, Treasurer and Librarian, and their adoption was moved by Mr. Alex. McLean. The following members were elected to the vacant seats on the Council: Dr. Ethel Currie, Prof. Dron, Prof. Macnair, Dr. Tyrrell, Mr. Duncan Smith and Mr. Eric Dow. The following new members were elected: Miss Eliz. Melville, Messrs. A. G. MacGregor, M.C., B.Sc., Chas. W. Duff, James Gardner, M.B. and Wm. H. Thomson.

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Mr. P. J. Robinson, A.M.Inst.C.E. read a paper on "The Pitchstone of Penrioch, Arran." (*See this Volume*, Part II).

Dr. Tyrrell, in welcoming this first contribution from Mr. Robinson, referred to the original technique developed by Mr. Robinson for the making of thin sections. Pitchstone is associated with tholeiite on Cir Mhor and at Tormore. Mr. Robinson was probably correct in interpreting the zenoliths as evidence of a similar association at Penrioch, but the tholeiite in this case has not been exposed.

A paper on "The Genus *Clisiophyllum*," by Prof. P. Macnair, F.R.S.E., F.G.S., and Mr. Colin M. Leitch, O.B.E., B.Sc., was read by Prof. Macnair.

Prof. Macnair outlined the history of the genus, and described the type species, *C. bipartitum*, McCoy. Clisiophyllid corals have been divided into many genera and species by authors, especially Thomson, and it was the purpose of the present communication to show that these can be reduced to four types of variation from a standard form—*C. bipartitum* being selected as having priority according to the ordinary rules of nomenclature. These four variants are—(1) The Dibunophyllid type; (2) The Koninckophyllid Type; (3) The Histiophyllid Type; (4) The Rhodophyllid Type, and are denoted vars. $\alpha$, $\beta$, $\gamma$, $\delta$ respectively. Prof. Macnair supported his thesis by observations on the ontogeny of the variants and their distribution in Scotland. For example, a section taken near the tip of a Rhodophyllid corallum shows a condition of the median lamella identical with that seen in the adult *Dibunophyllum*. All these types of variation are found in the Blackbyre and Hollybush horizons of the Scottish Carboniferous Limestone, and the material studied, which was derived from the Selkirk and Thomson Collections, was largely collected from these horizons.

The President said that some reduction in the number of Thomson's genera and species was doubtless justified, but perhaps Prof. Macnair had gone too far in reducing them to four varieties. What value did these varieties have as zonal indices?

Prof. Macnair, in reply, said that he had a precedent for the drastic reduction in the number of Clisiophyllid genera and species in the work of Dr. Stanley Smith, who had reduced the numerous species of *Aulophyllum* and *Cyclophyllum* to a single species—*Aulophyllum fungites*. The varieties were of no value as zonal indices, as they were all found together, for instance, in the Dockra Limestone.

M. MACGREGOR.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 8TH DECEMBER, 1927.

The third meeting of the seventieth session was held here this evening—Mr. MURRAY, MACGREGOR, *President*, in the chair.

Mr. A. Stevens continued his studies on the Geometry of Structure Lines. Mr. Stevens discussed the properties of great circles, and traced the courses of a number of great circles, determined to selected trends, e.g. the Appalachian and Variscan Lines lie along one great circle, on the surface of the Earth. Crossings of great circle trends on the Earth tend to concentrate about definite points. Each of these "nodes" has its antipodal equivalent. Mr. Stevens indicated six of these nodes, and traced some of the associated trends. Tensional features are not unlikely to have developed along great circles—e.g.

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along meridians, suggesting that the nodes represent former relatively stable positions of the poles. The reviving of Elie de Beaumont's great circle analysis of trend lines is justified for the sake of analysis, not in order to fit the facts to any preconceived theory.

In reply to Dr. Tyrrell and Prof. Macnair, Mr. Stevens said that compressional features may be expected to follow older tensional lines, and it follows that it is probably wrong to connect a given direction with a particular epoch of disturbance; correlation by similarity of trend is likely to be erroneous.

Mr. A. McLean exhibited specimens of *Telangium* and *Cyclopteris* from the Calciferous Sandstone of Wester Anstruther, Fife, The bed of sandy shale from which they came is seen between tide marks immediately south of the Dreel Burn. It lies a few feet above the lowest limestone of the series. This occurrence of *Telangium* at a horizon some 3800 ft. below the Hurlet is interesting.

The President and Prof. Macnair spoke.

M. MACGREGOR.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 19TH DECEMBER, 1927.

A special meeting of the Society was held here this evening—Mr. MURRAY MACGREGOR, *Prsident*, in the chair.

Mr. James Phemister, M.A., B.Sc., H.M. Geological Survey, delivered a lecture on "Geological Investigation by Means of the Torsion Balance." (See *Summary of Progress for* 1926, pp. 168-196, and *Mining Mag.*, Vol. xxxvii, pp. 263-265).

The Chairman, Prof. Gregory and Mr. Duncanson contributed to the discussion.

M. MACGREGOR.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 12TH JANUARY, 1928.

The fourth meeting of the seventieth session was held here this evening—Mr. MURRAY MACGREGOR, *President*, in the chair.

The President referred to the death, from exposure in the Cairngorms, of Mr. Thomas Baird, an associate member of the Society, and called upon Professor Gregory to express the sympathy of the Society to Mr. Baird's parents in their sad bereavement. Professor Gregory said:—

"We meet to-day under the shadow of a sad tragedy. Twelve months ago Glasgow Geology lost a promising Palaeonotologist when Leslie Currie was drowned in Burma. Now we have to deplore the loss, at the same early age of 22, of a man who had given promise of a brilliant career in Physical Geology. Thomas Baird not having completed the course for his Science degree had naturally not carried through any elaborate research; but he had done enough to show his powers of quick and accurate observation, his intellectual insight, and literary ability. Miss Neilson has found in one notebook his account of sections exposing layers of sand interbedded between boulder clay in the foundations of the Union Bank in Renfield Street. He was working on the volcanic necks at Yieldshields Hill near Carluke, where he was studying the inclusions and general petrography with some help from Dr. Tyrrell. The problems however which chiefly roused his enthusiasm were those connected with the mountain structure of the Southern Highlands. On his return from

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the University excursion to Pitlochry last spring he examined some Dalradian rocks east of Kinloch Rannoch. Later he returned to make fuller collections, and his study of this material would have thrown light on its correlation. His interest in mountain problems roused his enthusiasm for mountaineering, and to gain experience of climbing in snow and ice he made several winter excursions in the Southern Highlands. He no doubt hoped some day to have the opportunity of travel among some foreign mountain ranges of which the Geology is still unravelled. For such work Baird had exceptional advantages. He was strong, tough, well built, and could walk great distances carrying a heavy pack. The suggestion has been made that the recent excursion by Baird and Barrie was unjustifiably reckless; but it does not seem to me that they incurred any inexcusable risk. They were both capable climbers, and had promised to exercise due caution. When the mystery is solved it will probably be found that they had successfully accomplished their main programme and that the disaster happened in the descent from the last peak. From the indications available they appear to have met with one of those accidents to which all climbers on ice are liable. It probably happened along the Cairn Toul—Braeriach Ridge and during the descent from Braeriach on the way back to the croft from which they started on the expedition.

Death, when it strikes the young on the threshold of active life comes in its least acceptable form. On this occasion we have the consolation of the belief that Baird gave his life either in the effort to help Barrie to safety, or to find his comrade, if, as I suspect, they had been separated by an accident."

Professor Gregory moved that the Secretary be instructed to send a copy of the minutes in which these references to Mr. Baird's death were recorded, to Mr. Baird's parents. This was agreed to.

Prof. Arthur Holmes, University of Durham, delivered a lecture on Radioactivity and Continental Drift. (*See this Volume*).

Prof. J. W. Gregory said that some of the facts used in support of the theory of continental drift required to be etablished. For instance, with regard to the interpretation of the Matterhorn as a denuded remnant of the hinterland of Africa resting on Jurassic schists; were these schist really Jurassic? Many isolated facts of geology were difficult to explain on Wegener's theory. For instance, the Squantum Tillite (Boston) is situated on the line of Wegener's equator. The theory of convection currents in the sima was not open to many of the objections to Joly's theory.

Dr. G. W. Tyrrell said that Prof. Holmes' theory corresponded better with the facts of igneous geology than those of Joly and Jeffreys. Any movement on the continents would be reflected in the rhythm of igneous activity. Joly's theory demanded alternate world-wide fusion and solidification of the substratum, but there was no corresponding world-wide rhythm of igneous events. Prof. Holmes' theory, on the contrary, does not demand that fusion should be world-wide, and is therefore consistent with the local limitation of igneous episodes. What determined the inception and localisation of the convection currents?

Prof. Holmes, in reply, said that the late Mr. Lamplugh had worked out a theory of continental drift to explain the distribution of the Permo-Carboniferous glaciations. Like Prof. Gregory, he (Prof. Holmes) had been unable to find any evidence for the Jurassic age of the schists below the Matterhorn, but their precise age was not a matter of great importance. The Squantum

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Tillite was a difficulty on any hypothesis. There occured close together in that area alleged laterites, tropical coal-seams and glacial deposits. The difficulty lay in the interpretation of the facts themselves, and was possibly due to wrong stratal correlation. With regard to the localisation of convection currents, there would be four systems corresponding to the four divisions of Wegener's continent. Mr. Harrison's suggestion that sial might be present in the Pacific was not supported by the evidence of L earthquake waves and petrology.

Prof. Holmes was accorded a vote of thanks for his lecture, to which he briefly replied.

M. MACGREGOR.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 9TH FEBRUARY, 1298.

The fifth meeting of the seventieth session was held here this evening—Mr. MURRAY MACGREGOR, *President*, in the chair.

Mr. H. J. W. Brown, B.Sc., Purley, Surrey, was elected a member of the Society.

Pro . J. W. Gregory delivered a paper on " The Geology of Loch Lomond." (*See this Volume*).

Mr. Macnair said that the rocks of the area form a continuous series, without any break from N.–S. With regard to the structure of the region, he did not believe in Prof. Gregory's faults. The depression is simply a rock basin.

Dr. Tyrrell asked what were Prof. Gregory's views of the relation of the Lennoxian to the Highland Border Series. He agreed with Prof. Gregory in separating the Lennoxian from the Dalradian to the North, but on petrographic grounds he could not separate the Lennoxian from the Highland Border Series. The occurrence of fossils in the latter was the only difference.

The President said the origin of the basin was doubtless due to a combination of factors. It was out of alignment with the older valleys, therefore it was probably not an ice-deepened river valley. On the other hand he agreed with Mr. Macnair that there was very little evidence of faults.

Prof. Gregory, in reply, said he agreed there was a regular passage from the albite-gneisses, but debris of the schists in the slate-grit series afford evidence of an undoubted break. If there are no faults in the area, how can the twisting of the rocks at right angles to the normal strike be explained ? The Lennoxian is a distinctly older series than the Highland Border rocks, with more advanced metamorphism, but otherwise they are strikingly similar. He agreed that various causes had contributed to the formation of the basin, but faults were the prime factor in its origin. For various reasons the floor of the basin was not likely to afford conclusive evidence of origin.

M. MACGREGOR.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 8TH MARCH, 1928.

The sixth meeting of the seventieth session was held here this evening—Mr. MURRAY MACGREGOR, *President*, in the chair.

Mr. George Ross, B.Sc., H.M. Geological Survey, read a paper on " The Carboniferous Rocks of the Coalburn District of Lanarkshire."

The district is bounded on the west by the R. Nethan, and comprises an

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area of 18 sq. miles. The structure of the district was discussed and the detailed stratigraphy described from sketch maps and sections. Local variations were described and correlations and comparisons made with the Central Coalfields and the Glenbuck District. The formations represented are: (1) The Calciferous Sandstone Series; (2) The Lower Limestone Group; (3) The Limestone Coal Group, and (4) The Upper Limestone Group and the Millstone Grit. The Calciferous Sandstone comprises (1) a Lower Division of grits and red and yellow sandstone, conformable with the Upper Old Red, (2) a Middle Division of Marls and thin limestones, and (3) an Upper Division, of Scottish Carboniferous Limestone facies, with fossiliferous limestones, faikes, blaes, etc.

The zonal value of the following fossiliferous horizons was emphasized: *Productus giganteus* Limestone, Main Limestone (*P. giganteus*, ) just showing absence of furrowing in the unbonal region, *Posidononya corrugata*, Johnstone shell-bed, and Index Limestone. In the Upper Limestone Group the Orchard, Calmy, and Castlecary Limestones have been identified in bores.

Mr. Macnair said that the general stratigraphy of the Coalburn District is practically the same as at Lesmahagow. The main Limestone with the smooth *P. giganteus* is the Blackbyre Limestone.

Messrs. V. A. Eyles, B.Sc., J. B. Simpson, B.Sc. and A. G. MacGregor, M.C., B.Sc., read a paper on the "Igneous Geology of Central Ayrshire." (*See this Volume*).

Mr. A. G. MacGregor, M.C., B.Sc. read a paper on the "Classification of Scottish Carboniferous Olivine-Basalts and Mugearites." (*See this Volume*, Part II).

Dr. G. W. Tyrrell congratulated the authors of these papers on their work, and Mr. MacGregor briefly replied.

M. MACGREGOR.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 12TH APRIL, 1928.

The seventh meeting of the seventieth session was held here this evening—Mr. MURRAY MACGREGOR, *President*, in the chair.

Mr. William Downie, proposed by Mr. E. J. Edwards and Dr. Weir, was elected member of the Society.

Dr. J. F. Scott read papers on (*a*) Composite Dyke, Havock, Dumbartonshire, and (*b*) Some "Granite" Bosses of S.W. Scotland. (*a*) is an unrecorded member of the Carboniferous suite intrusive into Upper Old Red Sandstone. Its maximum width is 7 feet 3 ins., and it comprises two members of porphyritic olivine basalt. The second is chilled against the first and has altered it. Zones of slickenside and shattering show that movement had taken place after its intrusion. The central member is highly porphyritic, often vesicular, and contains inclusions of a fine-grained basalt. The country rock is decolourised for two feet from the margin and its calcareous cement is largely replaced by silica laid down in optical continuity with the original quartz grains.

(*b*) The petrology of the following intrusions was described:—Barncorkrie, Glenluce, Carsebuie, Barnaight, Doon Hill, Kirkinner, four near Creetown, Mid Burn, Mid Hill, Knockgray, Cairnsmore of Carsphairn, Harg Hill, Cairngarroch, and Knockencur. The first is the most basic, olivine appearing in one

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of its phases, and the last is the most acid. The others vary between Tonalite and Diorite, Augite-Biotite-Diorite being very common.

In the tectonics of the region a N.E.–S.W. alignment of the plutonic intrusions was pointed out. The Merrick and Kells mass is considered to have been two intrusions subsequently joined. The metamorphosed areas without any visible igneous contact show the same disposition, and coincide with the strike of the Lower Palaeozoic sediments.

Dr. Tyrrell congratulated Dr. Scott on his papers. He agreed with Dr. Scott's interpretation of the Havock dyke. Dr. Scott had made a promising beginning with the study of the petrology of the plutonic intrusions of S.W. Scotland and their structural relations. These coincide with the fold structures of the Caledonian mountain making.

The President congratulated Dr. Scott on his papers. The observation of the alignment of the intrusions and the metamorphic areas was new. To what degree had metamorphism proceeded in these areas?

Dr. Scott thanked the speakers for their remarks. In reply to the President he said there was very little metamorphism beyond a marked increase in secondary biotite.

Dr. G. W. Tyrrell read a paper on " Recent Scottish Earthquakes."

The Oban earthquake, December 23rd, 1925, 12.35 p.m. reached an intensity of about 6 on the Rossi-Forel scale in a small area between Oban and Tobermory, but was felt from Banffshire to Ayrshire. The isoseismals are elongated in a N.E.–S.W. direction, and the quake appears to have been due to movement along the Great Glen Fault near the intersection of Loch Linnhe with the Sound of Mull. A sympathetic shock took place near Bothwell, Lanarkshire.

The North Sea earthquake, January 24th, 1927, 5,20 a.m., was a considerable shock felt over practically the whole of Scotland, part of the North of England, and the greater part of Southern Norway. Phenomena indicating intensity 6 on the Rossi Forel scale were experienced in Aberdeenshire and neighbouring counties. In Peterhead and Aberdeen the overthrow of movable objects occurred to some extent, and it is probable that the isoseismal 7 skirted the coast. Isoseismal 6 runs from Montrose through Nairn, and then in a northeasterly direction east of the Caithness coast, the Orkneys, and the Shetlands. The earthquake was probably due to movement along a fault under the North Sea some distance to the west of Haugesund, Norway.

The Colintraive earthquake, three days later, January 27th, 1927, 9.03 a.m. reached an intensity of 5 in a small area centering about Colintraive on the eastern Kyle of Bute. To the S.E. it was felt as far as Ecclefechan, Dumfriesshire. The isoseismals are elongated in a N.W.–S.E. direction and the isoseismal axis runs along the eastern Kyle of Bute to Loch Gilp. An after shock which reached an intensity of 4 in an area elongated N.E.–S.W. along Loch Fyne and West Loch Tarbert occurred at 4.10 p.m. on the same day. These earthquakes seem to be due to movement in the rectangular network of fiord fissures in the region shaken.

The President congratualted Dr. Tyrrell on the results of his work.

M. MACGREGOR.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 11TH OCTOBER, 1928.

The first meeting of the seventy-first session was held here this evening—Mr. MURRAY MACGREGOR, *President*, in the chair.

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The President referred to the death of Dr. Horne, which had taken place since the last meeting of the Society in April, and asked that the Secretary be instructed to convey to Dr. Horne's daughter the sympathy of the Society in her bereavement. The President then delivered the second part of his Address on "Scottish Carboniferous Stratigraphy." (*See this Volume*).

Rev. Dr. Sibbald and Mr. A. McLean expressed the thanks of the Meeting to the President for his address.

M. MACGREGOR.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 8TH NOVEMBER, 1928.

Mr. MURRAY MACGREGOR, *President*, in the chair.

Mr. Duncan Leitch, proposed by Dr. J. Weir, and seconded by Dr. G. W. Tyrrell was elected a member of the Society.

*Annual Business Meeting.* Reports for the last session were presented by the Secretary, Librarian and Treasurer. In moving the adoption of the three reports, Mr. McLean paid tribute to the work of the officers of the Society. He recalled the painstaking work of Mr. Sinclair as librarian, and expressed the regret of the members that his successor, Dr. Ramsay Sibbald, was now compelled to reliquish the office. Dr. Tyrrell, who seconded, regretted that greater use is not made of the Society's excellent library. He noted with concern that the Secretary's report indicated that it will be necessary to suspend publication of the *Transactions* until funds have accumulated, and, pointing out that they are second in importance to those of the Geological Society of London alone, he hoped that means would be found to publish annually. He asked the Treasurer for more information as to the finances. Mr. Begg replied and the reports were adopted.

The Society then proceeded to elect the following office-bearers who had been proposed and seconded:—

Vice-President—Mr. J. E. Richey, M.C., B.A.

Secretary—Mr. B. Hilton Barrett, M.A., B.Sc., F.G.S.

Librarian—Mr. W. J. McCallien, B.Sc.

Council—Dr. J. Phemister, Mr. H. H. Roderick, Mr. J. C. Roberts, Mr. D. B. Duncanson.

The President reported that a letter of thanks had been received from Dr. Horne's daughter thanking the Society for its expressions of sympathy in her recent bereavement. Dr. G. W. Tyrrell was appointed to represent the Society on the Peach and Horne Memorial Committee.

On the motion of the President a vote of thanks for their excellent work on behalf of the Society was accorded to the retiring Secretary, Mr. Duncanson and Librarian, Dr. Ramsay Sibbald.

The following papers were presented. First:

"Notes on the Preparation of Rock Sections for Microscopical Examination." By P. J. Robinson, A.M.Inst.C.E.

A chip of rock about 1½ in. square is ground by hand on one face in the usual manner. The coarse grinding is carried out on a steel plate with No. 60 grit carborundum and water, followed by grinding on a zinc plate with No. 150 grit carborundum. The fine grinding is carried out on three pieces of plate glass charged respectively with FF carborundum, 600 grit grade "M" carborundum, and Swift's No. 8 "Quartz Wedge" emery. The lubricant used

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on these glass plates is a mixture of water 75 parts and glycerine 25 parts. In order that a harder and more tenacious cement than Canada Balsam may be used, the chip, instead of being attached to a standard microscopical slip, is cemented to a plate glass holder about 1¼ in. square and ground to finished thickness thereon. The cement used consists of 3 parts by weight of wax-free Shellac, and 1 part of natural Canada Balsam, dissolved to the thickness of treacle in a mixture of 2 parts chloroform and 1 part absolute alcohol. The wax-free shellac is prepared by dissolving flake orange shellac in 98 per cent. alcohol, filtering through a quick filtering paper and evaporating off the solvent on a water bath until a pliable solid results on cooling. Instead of the cement alone being cooked on a hot plate till the required degree of hardness is obtained and the chip then added and pressed down, the chip is placed on the raw cement and cooked along with it. This in effect is equivalent to boiling the chip in the cement and has obvious advantages. The grinding down of the chip to the required thickness is carried out successively on the plates and with the grades of abrasives previously mentioned. In the ultimate stage, if the section begins to break away at the edges due to its having become slightly convex, the holder plate is laid section up on the table and localised grinding carried out with a short length of glass rod about ¼ in. diameter which has one end ground on a flat.

After completion of the grinding, a small block of Plaster of Paris about 1 in. by 1¼ in. by ⅜ in. deep having a perfectly flat bottom face is cemented on to and over the section with gum-plaster cement. This cement is made by mixing a small quantity of the finest dental Plaster of Paris to a smooth, stiff paste with Gum Arabic mucilage compounded to the following formula:—

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|---|---|
| Gum Arabic .. .. | 45 gms. |
| White Sugar .. .. | 5 gms. |
| Glycerine .. .. | 2 c.cs. |
| Water .. .. .. | 50 c.cs. |

The plaster block must be of such a size and so placed on the section that the gum-plaster joint is in contact either with the section or the surrounding film of shellac-balsam cement.

After being allowed to set and harden for about 24 hours, the holder plate is placed on a hot plate to soften the shellac-balsam cement and the block pushed cautiously off.

The face of the section is cleaned free from all trace of the shellac-balsam cement with methylated spirit, and the block with the attached section re-mounted on standard 3 in. by 1 in. glass slip with cooked natural Canada Balsam in the usual manner.

The clip is then soaked in water for about an hour to soften the gum-plaster joint, the plaster block removed, the section cleaned free from remains of the gum-plaster cement by brushing with water, all superfluous balsam scraped away, and the section trimmed to size. After drying, a cover glass is affixed, without heat, using dried Canada Balsam in Benzol.

Dr. Tyrrell complimented the author on the excellence of his slides and on the care he had expended in perfecting his methods. The method of transferring a cut section from one slide to another was particularly valuable and a distinct advance on the old way of floating it across.

Mr. Robinson had a series of exhibits illustrating each step in the production

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of a slide. On the motion of the President a vote of thanks was accorded to Mr. Robinson for his paper. The second paper, "The Dykes and Associated Intrusions of the Island of Bute," by H. J. W. Brown, M.Sc., A.K.C., was read by Dr. G. W. Tyrrell. *(See this Volume).*

Mr. Richey spoke of the interesting features of the area and its position as a connecting link between the important areas to the north and south. He asked if it is possible to distinguish between a crinanite of Permian age and one of Kainozoic. Mr. A. G. MacGregor also spoke. Dr. Tyrrell in reply said that the Palaeozoic crinanites are richer in potash than the Kainozoic ones. A vote of thanks was accorded to Mr. Brown for his paper and to Dr. Tyrrell for communicating it.

M. MACGREGOR.

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Society's Rooms, 207, Bath Street, Glasgow, 13th December, 1928.

The third meeting of the seventy-first session was held here this evening—Mr. Murray Macgregor, *President*, in the chair.

The President intimated that nominations had been received for two new members, Mr. Prentice and Mr. Balsillie. The President also announced that an appeal for contributions to the new Publications Fund had been prepared and would be issued to members shortly.

Professor J. W. Gregory, President of the Geological Society, delivered a paper on "Islay." *(See this Volume).*

Mr. E. B. Bailey said that he had listened with much pleasure and little disagreement. He had not much personal knowledge of the Lewisian but he believed it to be such. The quotation on the Torridonian from Geikie referred only to the type area from which the Diabeg is absent. The Diabeg is present in Skye, and Clough, the only authority was of the opinion that the rocks in Colonsay and Oronsay are of that age. The rocks in the latter islands are the same as those in question in Islay. The Lewisian and the Torridonian are cut off from the rest of the island by a continuation of the Great Glen Fault. To the east of this he was not so certain of the position. He was impressed by the fact that Peach, Horne and Clough thought that the Bowmore rocks are Torridonian. He was of the opinion that the junction between the Bowmore and the other rocks was by a thrust, the Loch Skerrols Thrust. The Bowmore rocks are not the least like the Port Askaig and for this reason he disagreed with Green. He agreed with Professor Gregory that there is a fault cutting off the Jura Quartzite from the anticline of the Boulder Bed and its associates, and this fault cuts out the shales and dolomites with worms. The position at the Port nan Gallan unconformity is as stated by Professor Gregory.

Professor Gregory in reply said that he had seen the Diabeg and had compared the Isaly rocks with Clough's description and was satisfied that the bulk of them are different. He thought that too much work is placed on the Loch Skerrols Thrust; it seemed to be a reversed fault. Green in denying it went too far. Mr. Bailey and he seemed to take different views of Green's meaning. The presence of a fault separating the rocks of the south-east from those to the north-west simplified the interpretation, giving a normal ascending series. He differed from Mr. Bailey as to the position of the Schichallion Boulder Bed. It is younger than the Blair Atholl Series.

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On the motion of the President a vote of thanks was accorded to Professor Gregory for his paper.

M. MACGREGOR.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 10TH JANUARY, 1929.

The fourth meeting of the seventy-first session was held here this evening—Mr. MURRAY MACGREGOR, *President*, in the chair.

Mr. Balsillie, Mr. Prentice, Mr. Cairnie and Dr. H. H. Read were elected members. The President referred to the gratifying response already made to the appeal for the new Publications Fund and intimated the receipt of over £70. Mr. Wm. J. McCallien then delivered a paper on "The Metamorphic Rocks of Kintyre." (*See Geol. Mag.*, Vol. lxvi, 1929, pp. 140-1 and *Trans. Roy. Soc. Edin.*, Vol. lvi, Pt. II, 1929, pp. 409-436.

The President referred to the importance of the paper as the first definite and authoritative account of the area. This was the first evidence of fold-faults in the district. He thought it was correct to make use of local names and indicate the equivalence in other areas. The rocks associated with the Loch Tay Limestone seemed to be different from those in the type locality, but the same feature occurred in the Braemar district. He stressed this point because when we are dealing with slides it is important that we should be very sure of our correlations. He offered the suggestion that the rocks of a small area should be studied in the very greatest detail in order to produce a perfect description of every bed along the line of the slide. He did not think that the association of the rocks could be explained except by fold-faults. The window is also important; again there is dependance on the correct naming of the rocks. Every possible reason should be given for the identification decided upon. He congratulated the author very heartily on a paper which marks a big and important advance, and he looked forward to reading it in detail.

Mr. George Ross said that he had listened with great interest especially to the part which dealt with northern Kintyre, where much of the difficult geology of the area had been lucidly cleared up.

He expressed his great admiration of the clear diagrams and stereograms.

Mr. McCallien thanked the members for their kind reception of his paper. The President's suggestion of a highly detailed survey of a portion of one of the slides did not appeal to him; he pointed out that the area of the peninsula is 340 square miles.

On the motion of the President a hearty vote of thanks was accorded the speaker.

M. MACGREGOR.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 14TH FEBRUARY, 1929.

The fifth meeting of the seventy-first session was held here this evening—Mr. MURRAY MACGREGOR, *President*, in the chair.

Mr. W. R. Flett was elected member. The President intimated that the Publications Fund stands at £95.

Mr. J. L. Begg then delivered a paper "Trinucleus in the Girvan Area." (*See this volume*).

The President remarked that it was a long time since the Society had had a

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purely palaeontological paper. Dr. Weir congratulated the author on bringing the description of *Trinucleus subradiatus* as near completion as it ever will be. A flexible pygidium would certainly be a great advantage in rolling especially when the number of thoracic segments is small. He had examined a large number of enrolled specimens of *Phacops* but in every case the tail was flat. The whole question of the segmentation of the pygidium is speculative and can only be proved by finding a flexed example and of this he was not hopeful in the Girvan area. Mr. Begg thanked the members for their reception of the paper and mentioned that he knew one specimen from Drummock in which the whole pygidium was flexed.

"The Pre-Glacial Valleys of the Clyde and its Tributaries," by M. Macgregor, B.Sc.

The pre-glacial courses of the Clyde and its tributaries are as a rule less gorge-like and deeper than the present valleys and their accurate delimitation is of very great importance where coals are worked in their vicinity at a shallow depth. Special attention was drawn to the relation of the old Kelvin Valley to the valleys of the Clyde and other tributaries of the latter. The Kelvin Valley is over 100 feet deeper than the old Clyde channel, and this super-deepening has been attributed to glacial erosion. The suggestion was put forward that in the pre-glacial Clyde-Kelvin channels two different drainage systems are represented. The deep Kelvin hollow is possibly part of an early drainage system developed when the Clyde below Dumbarton became an obsequent river. At a later stage the Clyde became the important stream cutting backwards and extending its drainage area, while the Kelvin was merely a sluggish stream winding over its old alluvial flats.

"Account of a Gravitational Survey over part of the buried Kelvin Valley, near Drumry, Glasgow," by Dr. J. Phemister.

The detailed account of the survey is published in the *Transactions of the Royal Society of Edinburgh*, Vol. lvi, Pt. 1, 1929.

The President in welcoming Dr. Phemister's paper mentioned that the work had been done in the months of January and February between the hours of 7 p.m. and 2 a.m. It had proved the value of the balance in competent hands and while still in its infancy it gave valuable results. The Society was to be congratulated on getting the results. Professor Dron supported the President and also thanked him for his own paper. He asked how Kendall got his theory of Glacial erosion? He was of the opinion that the work would have had an even greater economic value if it had been carried on along the south front of the Ochils where coal working is still going on. One of the earliest mining disasters was due to the entry of water from the Forth. He asked if the Geological Survey had done any work in conjuction with the Inspectors of Mines in preparing plans of these old channels. The papers had a most important economic application.

The President replied that Professor Kendall's line does not appear to be the line of ice movement. No special plans of the buried channels have been prepared but on the new 6 inch sheets they are shewn by a special ornament.

Mr. Stevens complained that the Torsion Balance work was incomplete. Not enough discussion had been given to the reversal of direction of the junction of the Kelvin and the Clyde.

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Dr. Phemister in reply stated that he had accepted theory in all cases because he had got agreement between theoretical conclusions and the balance results where there was a check. It is certain that the isogams do not turn west as they should do if there is a channel. Towards Clydebank the rock surface undulates.

A hearty vote of thanks was accorded to Mr. Begg, Dr. Phemister and the President for their papers.

M. MACGREGOR.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 14TH MARCH, 1929.

The sixth meeting of the seventy-first session was held here this evening—Mr. MURRAY MACGREGOR, *President*, in the chair.

Mr. Robert M. Alexander was elected member. The President stated that the Publications Fund amounted to £98. 17s.

Dr. J. F. Scott, St. Andrew's University, then delivered a paper, "Notes on the Glacial Geology of the Fife District."

The speaker prefaced his remarks with a summary of the geology of the Fife district, and proceeded to discuss in detail the origin of (1) the St. Fort terraces, and (2) the drainage systems of (*a*) the lower Motray Water and (*b*) the Kingsbarns area.

The problems (1) and (2*a*) were considered to be closely connected. The Motray Water flows, along the normal part of its course, in a N.E. direction. Near St. Fort station it bends sharply at a right angle to the S.E., and joins the Eden near Gardbridge. This change in direction was thought to have been caused by an ice barrier which blocked the natural outlet to the N.E., and which deposited the mounds of sand and gravel near the station. The presence of this barrier prevented the formation of the '100 ft.' Raised Beach in that area, while in the south, where the country was free from ice, that beach is well developed.

The study of the Kingsbarns area included a description of Kittocks Den; the Kenly Water, the Kilduncan Burn, and the Kippo Burn together with their tributaries. The course of events was probably as follows. A lake, into which flowed the Kenly Water and the Kilduncan Burn, was drained to the N.W. by Kittocks Den. After cutting through the Boulder Clay the gorge there would be easily formed as it lies along the strike of the sandstones. Another stream also flowing in this direction occupied a hollow W. of Kingsbarns. A tributary of this stream draining the eastern slopes of the Kilduncan drumlin cut back into it and ultimately captured the waters of the Kilduncan Burn which was now meandering through the almost dry upper end of the lake. Assisted by a fault on the shore another tributary of this stream cut back until it captured the Kenly Water. With this increased volume of water it soon became more important than its parent stream which, in its turn, was robbed of its headwaters by the Kippo Burn which joins the sea near Cambo Ness. The dry gap occurs just west of Kingsbarns. The Kippo Burn is a unique example of a burn capturing its own headwaters. A tributary on the northern bank worked back on a semi-circular course and tapped the waters of its upper reaches. The tributary now forms part of the main stream and has left a dry valley at the head of the now much reduced parent water..

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The President remarked that the working out of drainage is both interesting and difficult. He had not himself first-hand knowledge of the area and regretted that Dr. Balsillie was not present. Professor Gregory said that his own knowledge was derived from a single visit to examine the kame described by Geikie at St. Andrews and Leuchars. His conclusion was that the formation was a drumlin and he was pleased that Dr. Scott agreed. It is not a kame but a ridge of gravel left by the denudation of gravel and there is no evidence of ice after the 100 ft. raised beach, as there is in the case of Glen Rosa in Arran. He was saitisfied with the confirmation of Dow's old view. He thought that the right angled bend in the Motray Water is due to the piling of gravels across the old valley; had it been due to Wormit ice we would have found moraines but he knew of none. He thought that the interesting case of the Kippo Burn had been correctly interpreted. He was very interested in this account of the area and hoped that Dr. Scott would go on to give a full description of the glacial geology. Mr. McLean recalled that he had travelled from Kincraig Point to Cellardyke and had been much impressed by the large boulders he had seen. He asked what is the explanation of the remarkable changes of dip and strike in the coast section, a section of great interest to the non-professional geologist.

Dr. Scott thanked Professor Gregory and Mr. McLean for their remarks and said that at Leuchars all the boulders are of fluvio-glacial origin except these in the boulder clay. Those on the coast come from the Lomond Sills. The President in moving a vote of thanks to Dr. Scott remarked that much more information is required on the Calciferous Sandstone Series of Fife and a comparison made with the Lothians.

M. MACGREGOR.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 11TH APRIL, 1929.

The seventh meeting of the seventy-first session was held here this evening—Mr. MURRAY MACGREGOR *President*, in the chair.

The President referred to the loss sustained by the Society through the death of Mr. Peter Macnair. He recalled his work both as Secretary and President on behalf of the Society and his work in Scottish Geology particularly in the Carboniferous rocks. The Secretary was instructed to convey the sympathy of the Society to his wife and family. The President called the attention of members to the appeal for the Peach and Horne Joint Memorial Fund and stated that the Society's Publications Fund amounted to £110. 2s.

A paper on "Glaucophane and Allied Minerals in Scottish Rocks," by Dr. Wm. Mackie was read by Mr. Barrett.

The examination of forty specimens of Torridonian rocks showed the presence of one possible glaucophane in association with twenty other heavy mineral species. It was ovoid in shape, pleochroic from violet to a fainter violet, and extinguished at a small angle with the longer axis of the oval. The Torridonian has been derived, at least in part, from the Moine, and a possible source of this (?) glaucophane is a sericite schist from between Loch Hope and Ben Hope in Sutherland, which contains a soad-amphibole, pleochroic from blue to muddy-yellow or green and extinguishing at 3°. At St. Fillans, Perthshire, in the Ben Ledi Grits, a blue platy mineral occurs. Crushing produces straight edged fragments, but the edges rarely correspond with the

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cleavage lines of the amphibole, so that the extinction angle is hard to determine, but angles of 20° and over have been observed. The pleochroism is from yellow or green and there is little doubt that the mineral is not glaucophane. Similar fragments possibly derived from this locus, are found in Upper Old Red residues from the Heads of Ayr, and in Carboniferous residues from Kilsyth, Auchenlea and Sanquhar. The Llandeilian and Caradocian greywackes of Bail Hill (Sanquhar), Leadhills, and especially those about three miles S.W. of Sanquhar on the road to Thornhill are rich in glaucophane. It occurs as scales extinguishing at 3° but as often showing straight extinction. The pleochroism is from indigo-blue to violet, or to yellow or colourless. This is believed to be true glaucophane.

The President welcoming the paper said that he did not recall glaucophane as being recorded in the alkaline members ot the borolanite suite to the east. Mr. Barrett said that he had had the privilege of looking at Dr. Mackie's slides and was certain that the mineral from the Sanquhar exposures was glaucophane. He exhibited a number of lantern slides on behalf of Dr. Mackie. On the motion of the President, Mr. Barrett was asked to convey to Dr. Mackie the hearty thanks of the Society for his paper.

" (*a*) Note on the geology of South Bute. (*b*) Note on a dyke, Loch Skiport, South Uist. (*c*) Rocks from the Flannan Islands," by W. J. McCallien, B.Sc.

(*a*) A diagrammatic sketch drawn from a point a short distance S. of the Hawk's Nib, and looking N. was used to illustrate the unconformity between the rocks of the Upper Old Red Sandstone and the Calciferous Sandstone Series. An unrecorded dyke of trachyte or mugearite on the shore at the columnar sandstone, 400 yards S. of Kilchattan Bay Pier was described and references were made to other igneous phenomena.

(*b*) An unrecorded dyke of olivine-dolerite was described from the western shore of Little Kettle Pool, Loch Skiport, South Uist.

(*c*) A collection of seventeen rocks from the Flannan Islands, 15 miles N. of W. of Gallon Head, Lewis, was exhibited. The specimens show that this group of islands is composed of rocks similar to those of the Long Island itself. The gneiss seems to represent the more basic members of the suite—hornblende- and biotite- rocks. Into these is intruded a varied series of pegmatites and graphic granites. Traversing the island is a basaltic dyke which has been eroded to form a small gully. The specimens were collected by Mr. Neil Murray, Assistant Lightkeeper at the Flannan Islands.

The President thanked Mr. MacCallien for his notes and referred to the importance of the dyke in association with the columnar sandstones.

" Heavy Residues of the Calciferous Sandstone Series of the Glasgow District, by B. Hilton Barrett, M.A., B.Sc., Carnegie Teaching Fellow, Glasgow University.

The Calciferous rocks of the district are divided into Upper and Lower Sediments by the lavas of the Clyde Plateau. The residues from the lower sediments vary considerably. In specimens from near Helensburgh zircon and apatite are sparse, tourmaline rare and garnet very abundant; at Dumbarton zircon is still sparse but apatite is very abundant, while garnet and rutile, were proved to be entirely absent. Near Kilsyth, one specimen showed the same association as at Dumbarton, yet the bed immediately above, and just below the lavas, contained abundant zircons and garnets with little apatite. In addition, some hypersthene is present. In the Ballagan Beds zircon, apatite, garnet, tourmaline and monazite are present.

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In the upper sediments the residues from the lavas to the horizon of the Blackbyre Limestone contain only zircon, rutile and tourmaline, but above the limestone apatite and monazite are present in addition. The only occurrence of garnet above the lavas which is known is in the exposures of the Craigmaddie Conglomerates on the Douglas Muir north of Clydebank. Associated with it is some (?) staurolite. Such minerals as kyanite and andalusite have not been observed. One piece of fluorspar was seen in a residue from the lower part of the upper sediments.

The President said that it was interesting to find different heavy mineral associations in the Upper and Lower Sediments. The Upper Sediments were laid down on an old land surface and the members overlap. In the Lower Sediments minerals from the Highlands were present but in the upper, the land barrier to the west prevented the apperance of these until the submergence at the top. Mr. McLean noted that metamorphic minerals were said to be absent but noted the mention of zircon as abundant. He understood that it was a metamorphic mineral. Mr. Roderick asked if the speaker knew a sandstone at Kilsyth and Mr. Roberts mentioned that rocks near the horizon of the Lady Ann Coal were exposed in a temporary excavation in Messrs. Shank's works at Barrhead.

Mr. Barrett thanked the members for their kind reception of his paper and said that he had spoken rather loosely of metamorphic minerals. The notable absentees are kyanite and andalusite.

The meeting closed with a vote of thanks to the speakers.

M. MACGREGOR.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 10TH OCTOBER, 1929.

The first meeting of the seventy-second session was held here this evening—Mr. MURRAY MACGREGOR, *President*, in the chair.

The President in wishing the Society a successful session expressed the hope that there would be an increase in the membership and called upon the members to endeavour to interest their friends in our work. He intimated that the Publication Fund now stands at £133. 2s. Mr. R. Angus Downie, Clyde Cottage, Wishaw, was elected member. The business of the evening consisted first of an Exhibition of Fossils from the Girvan District by Mr. J. L. Begg.

Mr. Begg gave a short historical account of the research in Trilobites beginning in 1771 with Walch who first used the term tribolite. In the early part of the nineteenth century several contributions were made but all were eclipsed by the great work of Barrande in 1853. A great increase in knowledge resulted from the discovery of *Triarthrus becki* for the nature and functions of the appendages then became known. The Ordovician and Silurian rocks of the Girvan district have long been famous as repositories of trilobites and two of the most ardent collectors were Macallum and Mrs. Gray. The recently published description of Mrs. Gray's collection by Dr. Cowper Reed is the latest addition to research in this fossil. Three points of interest are now established; (1) thirty-six species occur at Girvan which are not known from any other locality; (2) some Girvan genera are not known elsewhere in Britain but occur in other parts of the world, e.g. Bohemia and the Scania Peninsula; (3) some genera and species appear here at a much earlier date than in other parts of the British Isles while others are found at later times

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than is normal. This year Mr. Begg discovered a new species of *Phacops* not hitherto known at Girvan.

Dr. Weir mentioned that the order Hypoparia is no longer recognised by palaeontologists. He hoped that members would make full use of the splendid opportunity to view the beautiful collection exhibited. On the motion of the President a hearty vote of thanks was accorded to Mr. Begg for his paper and his kindness in showing part of his valuable collection.

Dr. G. W. Tyrrell then gave an account of his experiences on the University of Cologne Excursion in the Rhineland. The first ten days were devoted to the Devonian and Carboniferous of the northern part of the area visited, and the remainder of the time to the volcanics of the Eiffel. In the first part the geology was simple. The basement rocks are folded Devonian, very similar to those seen in Devon and Cornwall, and form part of the Rhenish Schiefergebirge. In spite of the folding and faulting the rocks are still highly fossiliferous and corals are to be picked up in the road metal. They then visited the German Black Country which has no resemblance to the industrial parts of England. The Carboniferous rocks there have a very high dip and the coals are worked like metalliferous deposits by overhead stoping. Many of the structures are so complicated that they have not been fully worked out. Cretaceous rocks were seen forming outliers on the Carboniferous. Cretaceous oysters are now found as fossils clinging to the Carboniferous pebbles which lay on the bottom of the Cretaceous sea. From Cologne they moved westward to the brown Miocene coals. These are unlike our coals for they occur in beds 45 and 125 ft. thick worked in quarries with faces one mile long by half a mile in the other direction. The visit is made by means of a passenger train. Much fossil wood is contained in the deposit. A daily output of 17,000 tons is obtained by means of steam shovels and from this 5,000 tons of briquettes are made, the decrease being due to the 64 per cent of water in the coal. The output is 105 tons per man per day, as opposed to 1½ tons of hard coal. The excursion then moved south from Cologne by motor char-a-banc to the Eiffel. In the Triassic rocks they saw a remarkable lead mine in which the galena occurred in patches in the soft white sandstone and also between the pebbles of three conglomerate bands. Associated with it is some copper in the form of azurite. The ore was deposited as ordinary veins in the underlying Devonian and spread out to form ellipses in the more porous rocks above over the lines of the fissures. They also saw Devonian rocks in which the limestones had been replaced first by marcasite then by limonite or haematite. To Dr. Tyrrell the cream of the excursion was in the Eiffel, where the volcanic and igneous geology was magnificent. The form of the craters and cones is often perfectly preserved on account of the late age of the phenomena. One of the many striking features is the crater lakes which were due to explosion. The explosion was not accompanied by the outpouring of much material but ash and so the craters are preserved. The lakes are circular and occur in the highest parts of the plateau. The largest of them is the Lake of Lasch; at one place on it $CO_2$ is still issuing from the water and it is consequently dangerous to bathe or boat during calm weather. Pleistocene volcanoes are also present and near the Rhine a wonderful mud flow is to be seen called the Trass, a white structureless rock comparable with the Loess. These volcanic muds are rich in lime and silica and the inhabitants excavate cave dwelling in them. Bombs occur in Eiffel volcanics and many of these are ultrabasic. Bombs were collected

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composed of olivine, of black mica and of hornblende and augite. These recalled strongly the bombs from the volcanics of Ayr and Fife.

Dr. Tyrrell also described certain phenomena seen on various excursions in Britain recently including excellent ripple marking in the Moine rocks at Mallaig. He exhibited a series of lantern slides illustrating the crater lakes of the Eiffel and the ripplemarks in the Moine and showed specimens from all the excursions.

Mr. A. G. MacGregor asked if the galena deposits are associated with any intrusions and whether anorthoclase is found with any of the bombs. Dr. Tyrrell said that there is sanidinite reported near the Lake of Lasch but this is claimed to be from gneiss highly pyrometamorphosed and brought to the surface by the vulcanism. He did not know if there were any magma associated with the galena. Mr. McLean recalled that the area had been visited by Sir Archibald Geikie and asked if Dr. Tyrrell had observed any fossil fish. He had been particularly pleased to see the photographs of the crater lakes. Dr. Tyrrell said that he had not seen any fish but they are reported to occur.

Mr. Richey expressed himself as satisfied with the ripple markings and thereafter the meeting closed with a hearty vote of thanks to Dr. Tyrrell. The members took the opportunity of examining the exhibits.

M. MACGREGOR.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 14TH NOVEMBER, 1929.

The second meeting of the seventy-second session was held here this evening —Mr. MURRAY MACGREGOR, *President*, in the chair.

*Annual Business Meeting.* Reports for the last session were presented by the Secretary, Treasurer and Librarian. The Society then proceeded to elect the following office-bearers:—

President: Mr. J. E. Richey, M.C., B.A., F.G.S.

Vice Presidents: Dr. J. Phemister, F.G.S.; Mr. D. B. Duncanson, B.Sc.; Dr. J. Weir, F.G.S.

Secretary: Mr. W. J. McCallien, B.Sc.

Librarian: Mr. W. R. Flett, B.Sc.

Members of Council: Mr. A. G. MacGregor, M.S., B.Sc.; Mr. D. Leitch, B.Sc. (Assistant Librarian); Mr. P. J. Robinson, A.M.Inst.C.E.; Mr. P. A. Leitch.

Mr. James Smith was elected an Associate Member.

On the motion of the President a vote of thanks was accorded to the retiring President and to Dr. Weir for their excellent work on behalf of the Society.

The following paper was then presented.

"A Contribution to the Geology of the Carboniferous Sediments of Kintyre," by William J. McCallien, B.Sc. and Robert B. Anderson. (*See Trans. Roy. Soc. Edin.*, Vol. lvi, Pt. iii, 1930, pp. 599-619.)

Mr. Murray Macgregor said that he had no doubt the Machrihanish Coalfield was of Carboniferous Limestone age and recalled some impressions of the underground workings in the mine—notably the 60 foot high galleries in the sandstone over the Main Coal. The mines were shut beneath the Kilkivan Coal owing to fires in the Main Coal. Sufficient attention had not been paid in the paper to the igneous rocks exposed at the northern side of the coalfield. These he has always considered to be Millstone Grit lavas. He would like to

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suggest that the term bauxitic clay be used only after consideration of the composition of the rock, otherwise it will be very misleading from an economic point of view. He remarked that correlation over 15 miles as the authors had attempted was very difficult. In Scotland it is often difficult to correlate strata ½ mile apart. Mr. A. G. MacGregor said that Simpson described bauxitic weathering of Calciferous Sandstone lavas in Ayrshire. As regards the disputed igneous rocks he reminded the authors that in Ayrshire the Millstone Grit lavas are of uniform type which could doubtless be used in deciding the nature of the Machrihanish rock. Dr. Tyrrell welcomed this new and instructive account of the Machrihanish Coalfield with its interesting correlations. He thought, until he heard Mr. MacGregor's remarks that this was the first account of bauxitic formation in Calciferous Sandstone times. From what he had seen in Kintyre he believed in the pre-Old Red Sandstone age of the Kintyre ridge.

Dr. Weir asked if Thomson's collection of Kintyre fossils was still in the collection of the Geological Survey.

Mr. McLean made references to the geology of Northern Ireland and referred particularly to the great unconformity between the Kainozoic lavas and the underlying Chalk.

The President remarked that it would be interesting if any of Macnair's faunas could be found in Kintyre. In Ayrshire he said felsite pebbles were common in the igneous conglomerates and he asked if any had been found in Kintyre. Analyses of the clays were essential before they could be termed bauxites. There was no doubt, he thought, that the lavas rise in a ridge in Tirfergus Burn, dividing the sediments into 2 basins for the shales to the west were evidently cut out by the lavas. He repeated Mr. MacGregor's warning that correlation over 15 miles is difficult.

Mr. McCallien in reply stated that the term bauxitic clay was used on advice given to the authors' in confidence. The question of the origin of the igneous rocks apparently overlying the coalfield he left until he had a further opportunity of examining the field and microscopic evidence as to their origin. No felsite pebbles had been sliced from the igneous conglomerates. As far as he was aware Thomson's collection was destroyed by the fire in the Dick Institute, Kilmarnock. On behalf of Mr. Anderson and himself he thanked the speakers for their criticisms and advice.

J. E. RICHEY.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 12TH DECEMBER, 1929.

The third meeting of the seventy-second session was held here this evening—Mr. RICHEY, *President*, in the chair.

Mr. Eyles and Mr. Simpson were elected members and Miss Duncan and Mr. Finnie were elected associate members.

The following paper was then delivered:

"The Development of the Campine Coalfield of Belgium," by David Adam. B.Sc., Lecturer in Mining, Glasgow University.

The history of the Campine as a mining field begins in 1901 when a bore was put down near the village of Axh to verify a geological theory that had been advocated at least as early as 1876, that there is an extension of the Coal Measures of the Westphalian coalfield under the Cretaceous and Miocene formations covering the whole of northern Belgium.

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The fact that the Cretaceous rested directly on the Silurian in the northern limb of the Brabant anticline pointed to extensive post-Carboniferous denudation, and it seemed, therefore, that the coal-bearing strata north of this anticline, if they had escaped denudation, would be found under the Cretaceous at a depth within reach of mining operations.

The boring carried out between 1901 and 1906 proved the existence of this concealed coalfield from the Dutch frontier near Maastricht to the Province of Antwerp. To the south the field is bounded by the Silurian anticline of Brabant and to the north by large faults which ultimately throw the coals to a depth of at least 4000 metres below the Trias in the great subsidence trough of Roermonde.

The workable coals are covered by an overburden of Cretaceous and more recent strata varying from 1000 ft. in the eastern part of the field to more than 2000 ft. in the western part. This overburden of sand, clay, and chalk is heavily water laden and required the use of the freezing process in shaft-sinking. The successful application of this process to depths of 2000 ft. and more with water pressures up to 63 atmospheres was a great achievement in engineering.

The work was interrupted by the German occupation of Belgium in 1914-18, but there are now eight collieries with large concessions in the field at or near the productive stage.

The conditions to be met called for a very large capital outlay not only in shaft sinking and in plant, but in the provision of miners' houses.

No expense has been spared in providing comfortable homes and attractive surroundings in the garden cities of the Campine. They prove that disfiguration of the countryside is not a necessary corollary of mining operations.

The President gave a short account of the possible correlations of the Belgian with the English and Scottish horizons and exhibited tables of strata. It seems as if the strata correspond to the Lower Productive Measures of Scotland. The top bed beneath the Cretaceous seems to be the fossil bed known as the Ginstone, indicating the rocks to be in the Lower half of the Productive Measures. Mr. Adam said that the Upper Measures of the Westphalian field were claimed in the Campine.

Mr. Roderick asked what were the diameters of the bores and shaft. Mr. Adam replied that the bore started with a diameter of 18 iches and at 6000 feet the diameter was 3½ inches. The diameter of the shaft was about 5 metres.

Mr. Leitch asked why it was necessary to carry the freezing mixtures through all the strata and what was done with the waste material. Mr. Robinson asked what was the distance between the freezing bores and the shaft.

Mr. Adam stated that the mines had not been long enough working to have much waste material. It was originally intended to freeze only the Kainozoic strata, but it was found necessary to freeze right down to the running sand on top of the Carboniferous. The diameter of the freezing ring is about twice the diameter of the shaft.

On the motion of the President a vote of thanks was accorded to Mr. Adam for his paper.

J. E. RICHEY

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 9TH JANUARY, 1930.

The fourth meeting of the seventy-second session was held here this evening —Mr. RICHEY, *President*, in the chair.

The following papers were then delivered:

(1) "Note on the Glaciation of the Aberfoyle District," by J. B. Simpson, B.Sc., H.M. Geological Survey.

In the wide basin of the River Forth between Buchlyvie and Lake of Menteith there is evidence that during the time of the "100 foot" sea there was a glacial re-advance on a considerable scale. Its limits are indicated by a well-marked moraine, 12 miles long, that can be traced from a point a mile west of the old road between Gartmore and Drymen and 3 miles north of the latter, eastwards to Arnprior, where it swings northwards across the valley of the Forth, and along the eastern shore of the Lake of Menteith. At Auchyle, beside the Port of Menteith, the moraine reaches higher ground and turning westwards can be traced for some distance. The part of the moraine west of Buchlyvie was first described as such by Renwick and Gregory. Though containing a certain proportion of angular boulders, the moraine is predominantly gravelly. In this respect it closely resembles the contemporaneous moraine described by the speaker and others in the Loch Lomond region.

The barrier fronting the Lake of Menteith rests on shelly marine clay at a height of 65 feet above sea level.

At Auchyle the cusp of the moraine above the 100 foot contour is not continuous with this barrier, but projects considerably further to the east. This gap is easily understood for at its point of maximum advance the glacier was actually contemporaneous with and discharged its load of debris into the sea that was forming beaches at about 100 feet above present sea-level in the eastward ice-free portion of the firth. The glacier, after a short retreat, maintained its position at the Lake of Menteith while the land was rising and the level of the sea dropped from 100 to 65 feet O.D.

The President congratulated Mr. Simpson on his lucid account of the glaciation of this region and expressed the hope that this was the beginning of a long piece of research which would result in one of the biggest glacial discoveries of Scotland. He asked the author to say a word or two on the 100-foot shells which had been moved twice.

Professor Bailey said that where Gregory and Renwick had made a good beginning Simpson had carried us a much longer way. He had never seen anywhere in Britain a moraine that could be traced so far as the Loch Lomond moraine. Professor Bailey suggested that the shells were not so much washed from the boulder clay as from the glacier where they were mixed up with the clay and poured out with them in the glacial streams. The fact that we find thoroughly marine shells living in the Loch Lomond district indicates that there was little or no ice in the Loch Lomond basin at the time. The Loch Lomond and Forth basins correlated with many parts of Scotland and we required a name for this stage in the glaciation. Prof. Bailey suggested that it should be known as the Loch Lomond stage. He described similar deposits in Southern Mull, probably of the same date as the Loch Lomond and Forth deposits.

Dr. Tyrrell described a well-marked raised beach at a height of 69 feet at Crosslet, ½ mile east of Dumbarton.

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Mr. Sinclair said that he had listened to Dugald Bell, Renwick and John Smith speaking on this moraine and he was glad to hear of further work being done on it. Mr. Simpson in reply said that Prof. Bailey's views on the history of the shells were also his own. The marine clays in Lake of Menteith at 65 feet were those of the 100 foot sea. He agreed that the Loch Lomond basin was free from ice when the shells lived in the adjoining sea. He had seen a raised beach at Crosslet.

(2) "The New Red Sandstone Rocks of Arran," by Dr. G. W. Tyrrell and B. H. Barrett, M.A., B.Sc. (Rep. Brit. Assoc. for 1927, Trans. Sect. C, pp. 324-325. Fuller description in "The Geology of Arran," Mem. Geol. Surv. Scotland, pp. 75-103).

The President congratulated the authors on their work and discussed the bearing of the Arran Permian rocks on the classification of the New Red Sandstone of Ayrshire.

Mr. Simpson said that the Permian of Ayrshire rested unconformably on the underlying Barren Red Measures but there are no actual exposures showing Permian on Carboniferous. The basaltic horizon probably agrees with the lava horizon of Ayrshire.

Dr. Tyrrell emphasised the suddenness with which the basalt comes into the Brodick Breccia. Though there is no actual junction in Ayrshire there is in Arran the section of the Corrie unconformity.

Professor Bailey said that the most recent addition to the stratigraphy of the rocks was the recognition of the basalt and agate horizons. It was possible that there were unconformities within the rocks themselves. In Ayrshire there was movement while the Permian was being laid down.

Mr. Barrett thanked the members for their reception of the paper.

J. E. RICHEY.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 13TH FEBRUARY, 1930.

The fifth meeting of the seventy-second session was held here this evening—
—Mr. RICHEY, *President*, in the chair.

The President referred to the award of the Murchison Fund of the Geological Society of London to Mr. John Smith and stated that the Secretary had congratulated Mr. Smith on behalf of the Society.

The President also intimated that a Sub-Committee from the Council had been appointed to consider the question of trying to increase our membership.

Dr. J. Phemister then delivered a paper on "The Investigation of Faults by means of the Torsion Balance."

Faults are abrupt, more or less vertical, dislocations in the earth's crust and their delimitation is of vital importance in mining fields. In some fields a fault may represent the boundary beyond which productive working can be carried only after expensive drilling or perhaps not at all; in certain oil fields location of a fault is preliminary to sinking a well. On the two sides of a fault of considerable throw or displacement rocks of different kinds are brought together and there is therefore usually a sudden small change in the force of gravity from one side of the fault to the other. Use is made of this fact in gravitational surveys and the method was illustrated by reference to results obtained by H.M. Geological Survey near Portobello, Edinburgh, where the Pentland Fault was traced for a quarter of a mile beneath a cover of raised beach and glacial deposits.

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The President said that the Society was greatly indebted to Dr. Phemister for his account of the Torsion Balance experiment and he suggested trying the balance over another fault in an area where known features are very plentiful.

Mr. Murray Macgregor asked what was the limit of difference in specific gravity on both sides of a fault that could be appreciated by the balance. In the coalfields the rocks on either side of a fault are very much alike.

Dr. Phemister said that with a throw of about 1000 ft. in would be possible to detect a difference of .1. In the Pentland Fault except for lavas there would have been no specific gravity difference, but if there is any difference it can usually be detected. In Persia, working in homogenous strata noticeable difference in specific gravity is obtained over anticlines and faults because as a rule older rocks are denser than younger ones.

Prof. Gregory congratulated Dr. Phemister on the remarkable progress made with the Torsion balance, which was contrary to the general expectations of most people before the balance was tried. At that time he urged the Geological Survey to take up the subject in order to try the balance under type conditions in this country before taking it into our mining dominions. Mr. Barrett asked if the balance can be used in a selective way in a faulted district with buried channels.

Dr. Phemister explained on the black-board how to interpret faults and buried channels. It is usually possible to discriminate sub-drift effects from geological structures. For the investigation of faults with the Torsion balance it is better to know to within 1 mile the position of the fault. The stations must be as close as 100 yards.

On the motion of the President Dr. Phemister was accorded a hearty vote of thanks.

Dr. H. H. Read, H.M. Geological Survey exhibited a suite of specimens from Central Sutherlandshire showing all stages in the permeation by granitic juices of different types of Moine Schists, with the production of synthetic gneisses comparable with those of Fenno-Scandia.

The President said that we were fortunate in having Dr. Read's demonstration, and asked why oligoclase was developed in the injection series.

Dr. Read said that the schists outside the complex are richer in potash than soda, but the injection was richer in soda and so formed oligoclase.

Prof. Bailey asked why garnet was developed.

Dr. Read said it was derived from hornblende or olivine.

Dr. Tyrrell asked what were the conditions giving rise to both pegmatite and aplite in the same fissure. Dr. Read has described a case of hybridism between an igneous rock and a metamorphic rock in which no homogeneity has been attained. In the Arran complex a hybrid rock has been formed which is indistinguishable from a normal igneous rock.

Dr. Read said that the first reason was that there were more mineralisers in the pegmatite than in the aplite. Secondly the aplite is later.

Mr. Murray Macgregor asked Dr. Read to say a few words about how the mixtures were produced.

Dr. Read explained the structure of the granodiorite as a dome going under the injected rock and the floor was indicated on the map.

The meeting closed with a vote of thanks to Dr. Read and members took the opportunity of examining the exhibits. J. E. RICHEY.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 13TH MARCH, 1930.

The sixth meeting of the seventy-second session was held here this evening—Mr. RICHEY, *President*, in the chair.

A paper was then read by Messrs. G. Ross, D. Tait and J. Pringle, H.M. Geological Survey, "On the Age of the lowest Silurian Rocks of the Hagshaw Hills and Lesmahagow Inliers."

The account, which embodies some of the results obtained during the recent re-survey of the areas, throws fresh light on the correlation of the rocks of the two districts. From the material collected by Mr. Tait, Mr. Pringle showed that the lowest rocks in the two areas were identical and referable to a horizon in the Ludlow, probably that of the Aymestry Limestone of Shropshire. He further demonstrated that a change of fauna took place in the Lesmahagow area at a horizon represented by a conglomerate in the Hagshaw Hills already noted by Mr. Ross. The new interpretation has brought the succession into closer harmony with that established in the type area of England and in the Pentland Hills.

The President thanked the authors for their description of this remarkable advance in our knowledge and asked Mr. Ross if strike-faulting could not be responsible for the curtailment of the succession in the Hagshaw Hills.

Prof. Gregory congratulated Mr. Pringle and Mr. Ross on their important contribution to the geology of the Lesmahagow district and remarked on the interest of Mr. Tait's collection from an area which has been so often examined for fossils. He was interested to see that Mr. Pringle's views agreed with those of Prof. Stamp, although discouraged by authorities like Prof. Jones. Mr. Ross's discovery of the stratigraphical break was important.

Mr. Pringle in reply thanked the members for their reception of the paper. He thought it would be better to define the top and bottom of the Downtonian as it is at present and leave it until a committee was appointed to decide whether it should go into the Silurian or Old Red Sandstone. Mr. Ross's discovery was important in showing the relation to the underlying beds.

In reply to the President Mr. Ross said that so many sections were available that strike-faulting would have been seen if present. The Yellow Sandstone of the Lesmahagow inlier has slightly transgressive relations to the underlying rocks.

On the motion of the President a vote of thanks was accorded to the authors of the paper.

(2) Mr. W. Manson read a paper "On the Discovery of *Listracanthus wardi* in Skipsey's Marine Band at Overtown near Wishaw."

Specimens of the spines of this fish have not hitherto been found in the Scottish Coal Measures, and their occurrence in Skipsey's Marine Band strengthens the correlation of this index horizon with the Mansfield Marine Band and its equivalents in the Coal Measures of England. Specimens of *L. wardi* were exhibited.

The President congratulated Mr. Manson on a fossil find of first class importance, and asked Mr. Pringle to speak on the correlation of the Skipsey and Mansfield horizons.

Mr. Pringle gave an account of these horizons and pointed to the recent discovery of corals and trilobites in South Wales. Mr. M. Macgregor recognised the enormous advance of Mr. Manson's discovery. Both Mr. Gibson and Prof. Bailey had hinted at the correlation for which evidence was now forthcoming.

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Prof. Bailey said he was grateful to Mr. Manson for his discovery which had a wide bearing on the correlation of the Coal Measures. Correlation by plants was extremely difficult and the Skipsey-Mansfield line goes across Kidston's zonal lines. In the distribution of Upper Carboniferous plants geographical differences were very important. Whereas Kidston thought the Millstone Grit of Wales was later than that of Scotland, Prof. Bailey thinks they are the same and that the geography of the times accounts for the flora of Scotland being poorer than the contemporary flora of the south. Mr. Manson's discovery will lead to promising results. Dr. Weir and Prof. Gregory also spoke.

Mr. Pringle said that *Listracanthus* is not confined to the Mansfield horizon. Specimens had been found at other horizons but *Listracanthus wardi* was confined to Mansfield or its equivalent. One specimen had been found 69 feet above Mansfield. The meeting closed with a hearty vote of thanks to the authors of the papers.

J. E. RICHEY.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 10TH APRIL, 1930.

The seventh meeting of the seventy-second session was held here this evening—Dr. WEIR, *Vice-President*, in the chair.

A paper, "Geological Aspects of the Channel Tunnel," was read by J. Pringle, Esq., H.M. Geological Survey. (*See* Nature, April, 1929, pp. 608-610).

Professor Gregory congratulated the speaker on his paper and asked if any information had been obtained on buried channels in the Straits of Dover. He recalled a paper of his dealing with the Straits of Dover as a buried channel. Mr. P. Leitch asked if it is intended to drive the main tunnel alone or to accompany it with a pilot tunnel.

Mr. Roderick asked if the river channel that may exist below the Straits of Dover had any connection with the channel which he understood had passed south of the Isle of Wight in Kainozoic times.

After Mr. Pringle had replied he was accorded a hearty vote of thanks.

J. E. RICHEY.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 9TH OCTOBER, 1930.

The first meeting of the seventy-third session was held here this evening—Mr. RICHEY, *President*, in the chair.

The following new members were elected:—A. R. Mitchell, Esq., and Matthew Glover, Esq.

The President reminded members that the Publications Fund was still open.

Mr. Murray Macgregor then took the chair and before calling on Mr. Richey to deliver his Presidential Address referred to his (the President's) work on Tertiary Igneous structures in Mull, Ardnamurchan, Skye, and Ireland, and exhibited a copy of the new memoir of the Geological Survey of Scotland on the Geology of Ardnamurchan. Mr. Richey then delivered his Presidential Address:

"Tertiary Ring-Structures in Britain."

The investigation of the Tertiary plutonic districts of western Scotland by the Geological Survey, begun many years ago by Harker in Skye and by Gunn in Arran, has been completed by the detailed mapping of Mull and Ardnamur-

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chan. In the latter areas an annular or arcuate form is characteristic of both minor and major intrusions of which two types are recognised. Thin sheets that dip inwards towards a common focus are termed cone-sheets. Plutonic masses, arranged like cone-sheets around a common centre, are evidently steep-sided and are called ring-dykes. Cone-sheets and ring-dykes often belong to the same centre. Sometimes there may be two suites of cone-sheets and ring-dykes. Such a complex as that of Ardnamurchan or Mull supplies another remarkable feature of the Scottish Tertiaries. In Ardnamurchan three great periods of centralised activity are recognised with three intruison-centres of successive ages; in Mull two such centres are known. The point in the investigation of the Tertiaries now reached renders it profitable to return to the earlier districts surveyed. In N.E. Ireland, where Tertiary plutonics were mapped some 60 years ago, it is now possible to recognise both ring-dykes and cone-sheets, the former best seen at Slieve Gullion, the latter at Carlingford In Skye, where in the first instance cone-sheets were discovered by Harker, it would seem not unlikely also that major intrusions of ring-dykes type occur. In Rum, the existence of an intrusion-centre is marked by cone-sheets and radial dykes. In Arran, both in the case of the Northern granite and of the Central complex ring-phenomena have been recently emphasized by Tyrrell.

The intrusion of cone-sheets and ring-dykes is considered to have been preceded, or accompanied, by the formation of ring-fissures. Only by definite fracturing can the orderly arrangement of the intrusions be explained. Such fractures are regarded as resulting from stresses set up in the roof of a restricted magma-reservoir. According to Anderson, increase of magma pressure in the reservoir would find relief in cone-sheet fracturing and uplift of the roof would result from the ensuing magmatic intrusions. On the other hand, decrease of pressure would lead to ring-fissures and roof-subsidence. That cone-sheets were directly connected with a magma reservoir is suggested by the prevalence of composite cone-sheets, which must have been fed from a source where magmatic differentiation was in progress. By plotting the downward continuations of suites of cone-sheets the approximate depth of the reservoirs may be gauged. For the second centre in Ardnamurchan the depth is estimated as about 3 or 4 miles.

The Chairman asked Professor Bailey to propose a vote of thanks to the President.

Professor Bailey said he was delighted to have the opportunity of proposing the vote of thanks to Mr. Richey and gave reminiscences of their work together in Mull. One of Mr. Richey's best rewards for his work was the mapping of the finest ring-dyke in the world, the Loch Ba Ring-dyke. Mr. Richey also had the opportunity of following up the Mull work in Ardnamurchan and in his holiday-times had been mapping in Skye and Ireland. Prof. Bailey remarked on how few ring-dykes are known in the world. They have been described from Iceland and are known in the Oslo region in Scandinavia where in the old days they were entirely overlooked by Brögger. There, half a dozen ring-dyke complexes have been mapped but not described. An example is known too in South Africa. It is remarkable that cone-sheets are known only in the British Isles.

Prof. Bailey then made a request that Prof. Jones should say a few words on some recent experiments which he has been making.

The Chairman asked Prof. Jones to describe his experiments.

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Prof. Jones briefly described the behaviour of moist sands under compression. The sands were compressed from above and series of radial cracks dipping inwards were developed at different pressures. These were shown to be analogous to the structures described in Tertiary igneous phenomena.

The Chairman thanked Prof. Jones and Prof. Bailey for their remarks and conveyed the thanks of the Society to the President for his address.

J. E. RICHEY.

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ROOM 24, THE ROYAL TECHNICAL COLLEGE, GEORGE STREET, 13TH NOVEMBER, 1930.

The second meeting of the seventy-third session was held here this evening, being a joint meeting with the Glasgow and West of Scotland Branch of the Institution of Mechanical Engineers and the University Geological Society—Mr. E. BRUCE BALL occupied the chair.

The following new members were elected:—

T. Hamilton; T. McMeekin; D. Sutherland, M.A., Ph.D.; and Miss Catherine Duncan, M.A., Associate Member elected Full Member.

Professor J. W. Gregory, LL.D., D.Sc., F.R.S., delivered the Thomas Hawksley Lecture on "The Machinery of the Earth."

Prof. Gregory thought that the earth could be regarded as a machine as it is a combination of various parts and is moving through space and revolving around its own axis in mechanical obedience to the major forces of the universe and without any conspicuous impulse or free will of its own.

Discussing meteorites Prof. Gregory said that they indicate the nature and relative proportions of the metallic and stony shells of the earth, and in the heavenly bodies of which they are parts there is no record of any temperatures above 4000° or 5000° F. The evidence of earthquakes shows that a large central core of the earth is liquid. After the crust of the earth had formed it was weak for a time and was contracting extensively, but by the beginning of the Cambrian it was so thick as to cut off the surface from being much affected by the earth's internal heat and was so strong that folding was restricted to narrow belts.

The earth could not be deformed beyond a limited amount or it would become unstable and ultimately fly to pieces. But with the wonderful automatic adjustments of the earth, as soon as deformation rendered the crust unstable stability was restored by relatively rapid movements by which the approximately spheroidal form was recovered. The convulsions during this process led to changes in the crust that were indispensible for its primary service. Two essential considerations regarding any machine were its function and its efficiency in the discharge of that function. The main function of the earth is to serve as the home of man, and the lot of man is dependent on the earth's movements in space and on its power of self-adjustment to the changing conditions, both internal and external.

The combined rotation and revolution of the earth determine the weather and thus control the earth as the home of man. The movements within the crust provided for our many needs. The sea acted as the great regulator of the atmosphere, and counteracted all the disturbing agencies; for if too much carbon dioxide were taken from the air the bicarbonates in the water were dissociated and the sea breathed it forth until the standard proportion was

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restored. If volcanic activity or forest fires added an injurious amount to the air, the sea absorbed the excess and retained it as bicarbonates. The atmosphere was thus maintained at the special composition necessary for human respiration. Man required dry land that had been drained and left available for his occupation. Thanks to the constant interaction of the unequally weighted crust and the shrinking interior, the surface was being lowered in some places and upheaved in others. The instability which we deplored when an earthquake shattered towns, renewed the slopes on which the habitability of the earth ultimately depended.

Mr. Richey proposed and Mr. Leitch seconded a vote of thanks to Prof. Gregory, and this was heartily accorded. A vote of thanks was accorded to the Chairman on the call of Mr. Ewen.

Tea was served after the meeting.

J. E. RICHEY.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 11TH DECEMBER, 1930.

The third meeting of the seventy-third session was held here this evening—Mr. RICHEY, *President*, in the chair.

The President referred to the death of Mr. John Smith and asked that the Secretary be instructed to convey to Mr. Smith's relatives the sympathy of the Society in their bereavement.

*Postponed Annual Business Meeting*: Reports for the last session were presented by the Secretary, Librarian and Treasurer. A discussion arose out of the Librarian's suggestion that more of our periodicals should be sent to the Mitchell Library. Dr. Phemister asked that the Librarian make a list of the Foreign and British publications received by the Society. Mr. Richey in asking for a vote of thanks to the Secretary, Librarian, and Treasurer remarked on the amount of work necessary in running such a Society as ours. Mr. Macgregor moved the adoption of the three reports and Mr. Leitch seconded.

The following new members of Council were then appointed: W. Q. Kennedy, M. Macgregor, H. Priestley, Rev. Dr. Ramsay Sibbald, J. B. Simpson.

In the absence of Mr. Conacher, who was to lecture on "A Group of Glacial Kettleholes on Loch Etive," Professor Bailey gave an address on the Symmetry of Crystals. Mr. Begg also remarked on the Symmetry of Starfish. On the call of Mr. Richey, Prof. Bailey was accorded a hearty vote of thanks.

Mr. Macgregor suggested that Mr. McMeekin might be willing to exhibit a working model of a colliery which he had prepared. Mr. McMeekin expressed his willingness to do so.

The meeting then adjourned.

J. E. RICHEY.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 8TH JANUARY, 1931.

The fourth meeting of the seventy-third session was held here this evening—Mr. RICHEY, *President*, in the Chair.

The President intimated a donation from Dr. Weir to the Publications Fund, which now amounts to £138. 2s.

Dr. Tyrrell read a paper on "The Economic Geology of Sands."

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Dr. Tyrrell first described the mineral composition of sands, pointing out that durability was the essential character of sand-forming minerals. He discussed the origin of sands, and described the processes of decomposition, disintegration, transport, and deposition, which result in the formation of sands. Sands are found to differ in four general characters: mineral composition, grain size, assortment, and shapes of grains. The various industrial uses of sands were then described and explained. Sands for various minor uses are gem sands, sands containing rare earth minerals such as monazite, sands for agricultural work, for abrasives, road-materials and water-supply. The principal industrial uses of sands are as refractories, furnace and foundry sands, and for the manufacture of glass. A good moulding sand has to satisfy two apparently contradictory requirements. It must be cohesive so as to retain the shape of the mould, yet it must be open and permeable so as to allow the gases and liquids generated by the molten metal to escape. The treatment of the natural or " green " moulding sand in order to meet these requirements was explained. The requirements of glass sands are quite different; they must have very high silica content, with negligible iron, magnesia, or lime, and the grains must be even-sized and as rounded as possible, so as to ensure uniform and rapid melting of the batch.

Mr. Richey said we were greatly indebted to Dr. Tyrrell for his clear and interesting descriptions and a hearty vote of thanks was accorded.

2. Exhibition of a Model of Colliery Workings, by T. McMeekin. Before exhibiting the model Mr. McMeekin described with the aid of maps and plans the structure of the Colliery. The anthracite of the colliery was generally thought to have been formed by the heat from a whin sill, but as there are no igneous rocks in the area Mr. McMeekin's view is that the anthracite is due entirely to pressure and structural causes. He also explained the unusual behaviour of a large fault traversing the Colliery. Mr. McMeekin then described a model of an English Colliery which was also on exhibition.

Before members examined the models Mr. Richey expressed the Society's thanks for the interesting exhibit and a vote of thanks was accorded to Mr. McMeekin.

J. E. RICHEY.

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SOCIETY'S ROOMS, 207, BATH STREET, GLASGOW, 12TH FEBRUARY, 1931.

The fifth meeting of the seventy-third session was held here this evening—Mr. RICHEY, *President*, in the chair.

The following new members were elected:—

G. V. Wilson, B.Sc.; J. G. C. Anderson; A. Lamont, M.A.

On behalf of the Society the President congratulated Dr. Tyrrell on being awarded the Murchison Medal by the Geological Society of London.

Mr. Conacher then gave an address on " Oil Shales and the Scottish Shale Industry."

In consequence of the fact that the Scottish Mineral Oil Industry has for more than half a century utilised shale as its raw material, the term " oil shale" has been applied in commercial circles to a rather wide group of materials which agree in the one character of yielding somewhat similar products by distillation, but many of which do not fall within the scientific category of shale, i.e., clay rock fissile along the bedding planes. The essential character

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of oil shales from the commercial point of view is the quantity and nature of the organic matter, and in considering the subject from the economic point of view, it is obviously unsound to fix the boundaries of the group simply on the basis of the quantity and nature of the ash, which is more or less an accidental ingredient.

These materials can be arranged roughly in groups agreeing approximately in the nature of organic matter and product, and such groups are found to include materials which are truly shales containing, say, 80 per cent. of ash, and others which are not, e.g., the oil shales of the Lothians contain about 80 per cent. of mineral matter, and yielding oil fairly similar to that got from the brown Boghead Coal which contains no more than 25 per cent. of mineral matter and is generally classed as a Cannel Coal. Again the common black cannel coals are at one end of a group which contains at the other the cannel shales such as the Kiltongue Musselband or Lillie's Coal-Shale. Similarly with younger materials, e.g., the Kimmeridge Blackstone and shale, but in this case the presence of a very large percentage of sulphur put the distillation product in a separate category along with those from the shales of Liassic age from Somerset.

Looking abroad, a close approach to the characters of the Lothian shale is found in the Kainozoic shale of Nevada, while the shale of similar age from Burmah, with a lithological resemblance, differs markedly in the nature of its products. In Eastern Canada and the U.S.A. there occur wide stretches of black shale of Devonian age, in which the characteristic organic material is a spore-like body apparently identical with that occurring in the Tasmanite, formed at a similar period in Tasmania, but of marine origin with a sandy matrix. In Estonia, the single seam of Ordovician age contains materials of varying lithological character and the oil is of a peculiar type, rich in benzenes and therefore an attractive source of engine fuel and a bad one for lamp oil. A further class is that yielding asphaltic products, of which the types may be taken as the Albert Shale of New Brunswick and Nova Scotia (Carboniferous) the Kainozoic Flaggy Limestone of Colorado, Utah, and Wyoming and the diatomaceous beds of California. In the last-named case the dark brown or black structureless rocks of the surface are found at no great distance to be the source of the highly asphaltic petroleum of the Santa Maria field, and considering both laboratory and field evidence it is difficult to arrive at any conclusion except that the Rocky Mountain Shales are nothing but flaggy limestones impregnated with petroleum residues.

From the diversity of the materials thus briefly dealt with it will be apparent that economic utilisation is in each case a separate problem both technically and commercially. The technical methods applied to the Scottish Shale were depicted in the cinematograph film which was then shown.

In the absence of Mr. Richey, Mr. Duncanson expressed the Society's thanks to Scottish Oils, Ltd., to Mr. Conacher, and to the operators for their interesting programme. The meeting closed with a hearty vote of thanks.

J. PHEMISTER.

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# ABSTRACT

OF THE

# TREASURER'S ACCOUNTS.

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# GEOLOGICAL SOCIETY OF GLASGOW.

## THE TREASURER'S ABSTRACT OF ACCOUNTS FOR THE YEAR ENDING, 30TH SEPTEMBER, 1928.

### RECEIPTS.

| | | | |
|---|---|---|---|
| To Balance on hand 30th Sept., 1927:— | | | |
| Cash in hand .. .. .. | £14 3 3 | | |
| Balance in Bank .. .. .. | 34 17 7 | | |
| | | £49 | 0 10 |
| ,, Subscriptions:— | | | |
| Ordinary Members—78 at 15/- .. | £58 10 0 | | |
| Lady Members—7 at 10/- .. | 3 10 0 | | |
| Associate Members—8 at 2/6 .. | 1 0 0 | | |
| Arrears—4 at 15/- .. .. | 3 0 0 | | |
| | | £66 | 0 0 |
| ,, Interest on Invested Funds:— | | | |
| £250 War Stock (including Cowie Prize Fund) .. .. .. | £12 10 0 | | |
| Funding Loan (James Neilson) .. | 3 4 0 | | |
| | | £15 | 14 0 |
| ,, Deposit Receipt Interest .. .. .. .. | | 0 | 13 10 |
| ,, Sale of *Transactions* .. .. .. .. .. | | 6 | 7 7 |
| | | £137 | 16 3 |

### EXPENDITURE.

| | | | |
|---|---|---|---|
| By Library:— | | | |
| Geological Magazine .. .. | £1 10 0 | | |
| *Transactions* Vol. XVIII, Pt. 1 £70 0 0 | | | |
| *Less* paid by Mitchell Library 4 13 5 | | | |
| | £65 6 7 | | |
| | | £66 | 16 7 |
| ,, Subscriptions:— | | | |
| Palaeontographical Society .. .. .. | | £1 | 1 0 |
| Scottish Marine Biological Association .. .. | | 1 | 1 0 |
| Natural History Society (for use of Lantern) .. | | 1 | 1 0 |
| ,, Cowie Prize Fund:— | | | |
| Glasgow University Geological Dept. .. .. .. .. | £2 10 0 | | |
| Royal Technical College (Interest to Mart. 1927) .. .. | 2 10 0 | | |
| | | £5 | 0 0 |
| ,, Administration:— | | | |
| Rent, Lighting, Fire Insurance and Attendance .. .. .. | £17 10 0 | | |
| Printing, Stationery and Postages | 14 15 11 | | |
| Hon. Secretaries', Treasurer's and Librarian's expenses .. | 5 14 8 | | |
| | | £38 | 0 7 |
| ,, Professor Arthur Holmes' expenses .. .. .. | | £3 | 10 6 |
| ,, Balance on hand:— | | | |
| Cash in Bank .. .. .. | £2 18 2 | | |
| Cash in hand .. .. .. | 18 7 5 | | |
| | | £21 | 5 7 |
| | | £137 | 16 3 |

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## BALANCE SHEET.

| | | | |
|---|---|---|---|
| To Life Subscription Account .. .. .. .. | £256 | 0 | 0 |
| ,, Cowie Prize Fund .. .. .. .. .. | 101 | 15 | 0 |
| ,, Capital .. .. .. .. .. .. .. | 579 | 2 | 7 |
| | £936 | 17 | 7 |

| | | | |
|---|---|---|---|
| By Investments:— | | | |
| War Stock, 1927-1949 (including Cowie Prize Fund) .. .. .. .. .. .. | £250 | 0 | 0 |
| Funding Loan (James Neilson) .. .. .. | 100 | 0 | 0 |
| National Saving Certificates .. .. .. | 65 | 12 | 0 |
| ,, Property:— | | | |
| Books, Furniture and Microscope .. .. | 500 | 0 | 0 |
| ,, Balance—Cash in Hand .. .. .. .. | 21 | 5 | 7 |
| | £936 | 17 | 7 |

GLASGOW, *26th October*, 1928.—Examined, compared with relative Vouchers and Securities, and found correct. The Balance on Hon. Treasurer's hands being Eighteen pounds, Seven shillings and Five pence.

(*Signed*) ARCHIBALD MACINTYRE, F.S.A.A.
ALEXANDER McLEAN. } Auditors.

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# GEOLOGICAL SOCIETY OF GLASGOW.

## THE TREASURER'S ABSTRACT OF ACCOUNTS FOR THE YEAR ENDING 30TH SEPTEMBER, 1929.

### RECEIPTS.

| | | | |
|---|---|---|---|
| To Balance Cash in Bank .. .. | £2 18 2 | | |
| Cash on Hand .. .. .. | 18 7 5 | | |
| | | £21 | 5 7 |
| ,, Subscriptions:— | | | |
| Ordinary Members—75 at 15/- .. | £56 5 0 | | |
| Ladies—7 at 10/- .. .. .. | 3 10 0 | | |
| Arrears—2 at 15/-.. .. .. | 1 10 0 | | |
| Associate Members—4 at 2/6 .. | 0 10 0 | | |
| | | £61 | 15 0 |
| ,, Investments:— | | | |
| War Stock (including Cowie Prize Fund) .. .. .. .. | £12 10 0 | | |
| Funding Loan (Jas. Neilson) .. | 3 4 0 | | |
| | | £15 | 14 0 |
| ,, Insurance and Actuarial Society of Glasgow:— | | | |
| Sale of Bookcase .. .. .. .. .. | | £10 | 0 0 |
| ,, Sale of *Transactions*, etc. .. .. .. .. | | 9 | 12 3 |
| ,, Publication Fund .. .. .. .. .. | | 133 | 2 0 |
| | | £251 | 8 10 |

### EXPENDITURE.

| | | | |
|---|---|---|---|
| By *Transactions*:— | | | |
| Titus Wilson & Son—Balance due for Volume XVIII, Part 1 .. | £67 5 6 | | |
| *less* Mitchell Library .. .. | 1 18 5 | | |
| | | £65 | 7 1 |
| ,, Library:— | | | |
| Geological Magazine .. .. | £1 10 0 | | |
| Expenses .. .. .. .. | 3 0 0 | | |
| | | £4 | 10 0 |
| ,, Subscriptions:— | | | |
| Palaeontographical Society .. .. .. | | £1 | 1 0 |
| Scottish Marine Biological Association .. .. | | 1 | 1 0 |
| Natural History Society (use of lantern) .. | | 1 | 1 0 |
| ,, Cowie Prize Fund:— | | | |
| University Geological Dept. (Interest to Mart., 1928) .. | £2 10 0 | | |
| Royal Technical College (Interest to Mart., 1928) .. | 2 10 0 | | |
| | | £5 | 0 0 |
| ,, Administration:— | | | |
| Rent, Lighting, Attendance and Insurance .. .. .. | £16 15 0 | | |
| Printing, Stationery and Postages | 16 5 10 | | |
| Hon. Secretaries', Treasurer's and Librarian's Expenses .. | 2 9 11 | | |
| | | £35 | 10 9 |
| ,, Balance on Hand:— | | | |
| Deposit Receipt (Publication Fund) .. .. | | £133 | 2 0 |
| Cash in Bank .. .. .. .. .. | | 1 | 9 5 |
| Cash on Hand .. .. .. .. .. | | 3 | 6 7 |
| | | £251 | 8 10 |

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## BALANCE SHEET.

| | | | | | |
|---|---|---|---|---|---|
| To Life Subscription Account .. .. .. .. | £256 | 0 | 0 | By Investments:— | |
| ,, Cowie Prize Fund .. .. .. .. .. | 101 | 15 | 0 | War Stock 1927-49 (including Cowie Prize Fund) | £250 0 0 |
| ,, Publication Fund .. .. .. .. .. | 133 | 2 | 0 | Funding Loan (James Neilson) .. .. .. | 100 0 0 |
| ,, Capital .. .. .. .. .. .. .. | 552 | 13 | 0 | National Saving Certificates .. .. .. | 65 12 0 |
| | | | | Property, Books .. .. .. .. .. | 440 0 0 |
| | | | | Furniture and Microscope .. .. .. | 50 0 0 |
| | | | | ,, Balance:— | |
| | | | | Deposit Receipt .. .. .. .. .. | 133 2 0 |
| | | | | Cash in Bank .. .. .. .. .. | 1 9 5 |
| | | | | Cash on Hand .. .. .. .. .. | 3 6 7 |
| | £1043 | 10 | 0 | | £1043 10 0 |

GLASGOW, *24th October*, 1929.—Examined, compared with relative Vouchers and Securities, and found correct. The balance on Hon. Treasurer's hands being Three pounds, six shillings and seven pence.

(*Signed*) ARCHIBALD MACINTYRE, F.S.A.A.
ALEXANDER MCLEAN. } Auditors.

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# GEOLOGICAL SOCIETY OF GLASGOW.

## THE TREASURER'S ABSTRACT OF ACCOUNTS FOR THE YEAR ENDING 30TH SEPTEMBER, 1930.

### RECEIPTS.

| | | | |
|---|---|---|---|
| To Balance Cash on hand | £3 6 7 | | |
| Balance Cash in Bank | 1 9 5 | | |
| | | £4 16 0 | |
| Deposit Receipt (Publication Fund) | | £133 2 0 | |
| ,, Subscriptions:— | | | |
| Ordinary Members—73 at 15/- | £54 15 0 | | |
| Ladies—7 at 10/- | 3 10 0 | | |
| Associate Members—7 at 2/6 | 0 17 6 | | |
| Associate Members Arrears—2 at 2/6 | 0 5 0 | | |
| | | £59 7 6 | |
| ,, Royal Society Grant for *Transactions* | | £50 0 0 | |
| ,, Publication Fund | | 3 0 0 | |
| ,, Investments:— | | | |
| War Stock (including Cowie Prize) Fund | £12 10 0 | | |
| Funding Loan (James Neilson) | £3 3 0 | | |
| | | £15 13 0 | |
| ,, Deposit Receipt Interest | | 4 14 3 | |
| ,, Sale of *Transactions* | | 7 10 7 | |
| ,, Balance due Treasurer | | 21 17 1 | |
| | | £300 0 5 | |

### EXPENDITURE.

| | | | |
|---|---|---|---|
| By *Transactions*, Vol. XVIII, Pt. 2 | | | £73 2 4 |
| ,, Library:— | | | |
| Geological Magazine | | | 1 10 0 |
| ,, Subscriptions:— | | | |
| Palaeontographical Society | | | 1 1 0 |
| Scottish Marine Biological Association | | | 1 1 0 |
| Natural History Society (use of Lantern) | | | 1 1 0 |
| ,, Cowie Prize Fund:— | | | |
| University Geological Dept. Interest to Martinmas, 1929 | £2 10 0 | | |
| Royal Technical College Interest to Martinmas, 1929 | 2 10 0 | | |
| | | £5 0 0 | |
| ,, Administration:— | | | |
| Rent, Lighting, Insurance and Attendance | £16 15 0 | | |
| Printing, Advertising, Stationery | £12 7 9 | | |
| Hon. Secretaries', Treasurer's and Librarian's expenses | 2 0 4 | | |
| | | £31 3 1 | |
| ,, Balance on Hand:— | | | |
| Deposit Receipt a/c (Publication Fund) | | £136 2 0 | |
| Deposit Receipt a/c (Royal Society Grant) | | 50 0 0 | |
| | | £300 0 5 | |

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## BALANCE SHEET.

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| To Life Subscription Account | .. | .. | .. | .. | £256 | 0 | 0 | By Investments in War Stock, 1927-1949 (including Cowie Prize Fund) | .. | .. | £250 | 0 | 0 |
| ,, Cowie Prize Fund | .. | .. | .. | .. | 101 | 15 | 0 | ,, Funding Loan (Jas. Neilson) | .. | .. | 100 | 0 | 0 |
| ,, Publication Fund | .. | .. | .. | .. | 136 | 2 | 0 | ,, National Saving Certificates | .. | .. | 65 | 12 | 0 |
| ,, Royal Society Grant | .. | .. | .. | .. | 50 | 0 | 0 | ,, Property, Books | .. | .. | 440 | 0 | 0 |
| ,, Balance due Treasurer | .. | .. | .. | .. | 21 | 17 | 1 | Furniture and Microscope | .. | .. | 50 | 0 | 0 |
| ,, Capital | .. | .. | .. | .. | 525 | 19 | 11 | ,, Deposit Receipts | .. | .. | 136 | 2 | 0 |
| | | | | | | | | ,, Deposit Receipts | .. | .. | 50 | 0 | 0 |
| | | | | £1091 | 14 | 0 | | | | | £1091 | 14 | 0 |

GLASGOW, *27th October*, 1930.—Examined, compared with relative Vouchers and Securities, and found correct. The Balance due Hon. Treasurer being Twenty-one pounds, Seventeen shillings and One penny.

(*Signed*) ARCHIBALD MACINTYRE, F.S.A.A. } Auditors.
ALEXANDER MCLEAN.

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